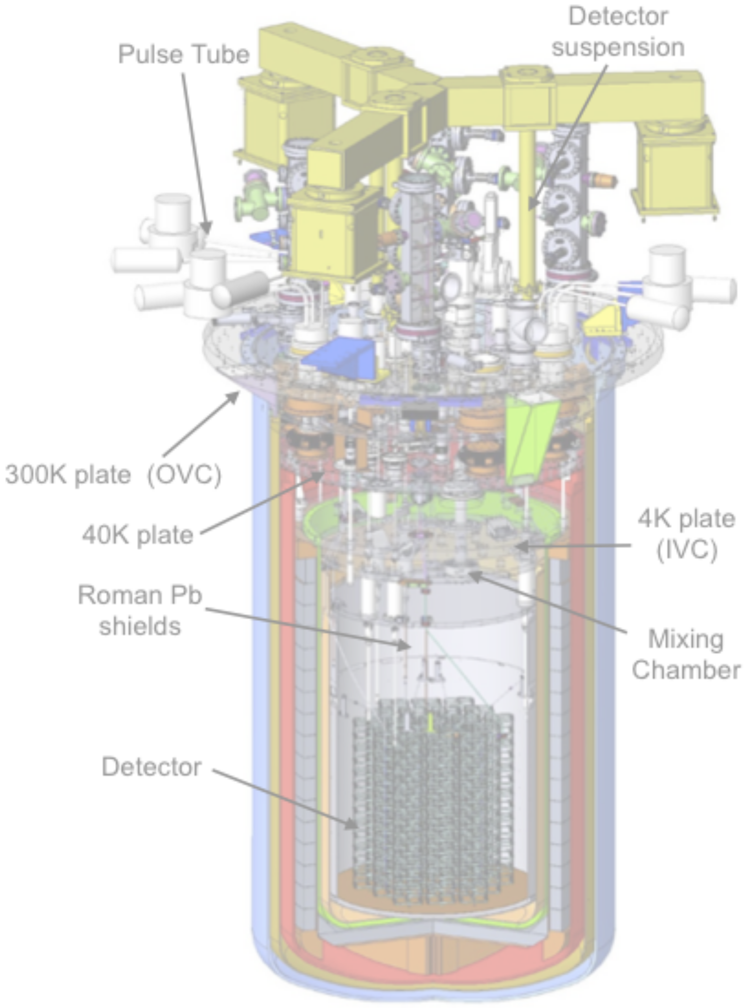
Neutrinoless ββ decay @ LNGS



99th Plenary ECFA meeting

June 30, 2016 - LNGS

Carlo Bucci

INFN - Laboratori Nazionali del Gran Sasso

INFN Istituto Nazionale di Fisica Nucleare

Present knowledge about neutrinos

- neutrinos are massive fermions
- there are 3 active neutrino flavors (ν_α)
- neutrino flavor states are mixtures of mass states (ν_k)

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k}|\nu_k\rangle$$

Pontecorvo–Maki–Nakagawa–Sakata matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric / Accelerator

Reactor / Accelerator

Solar / Reactor

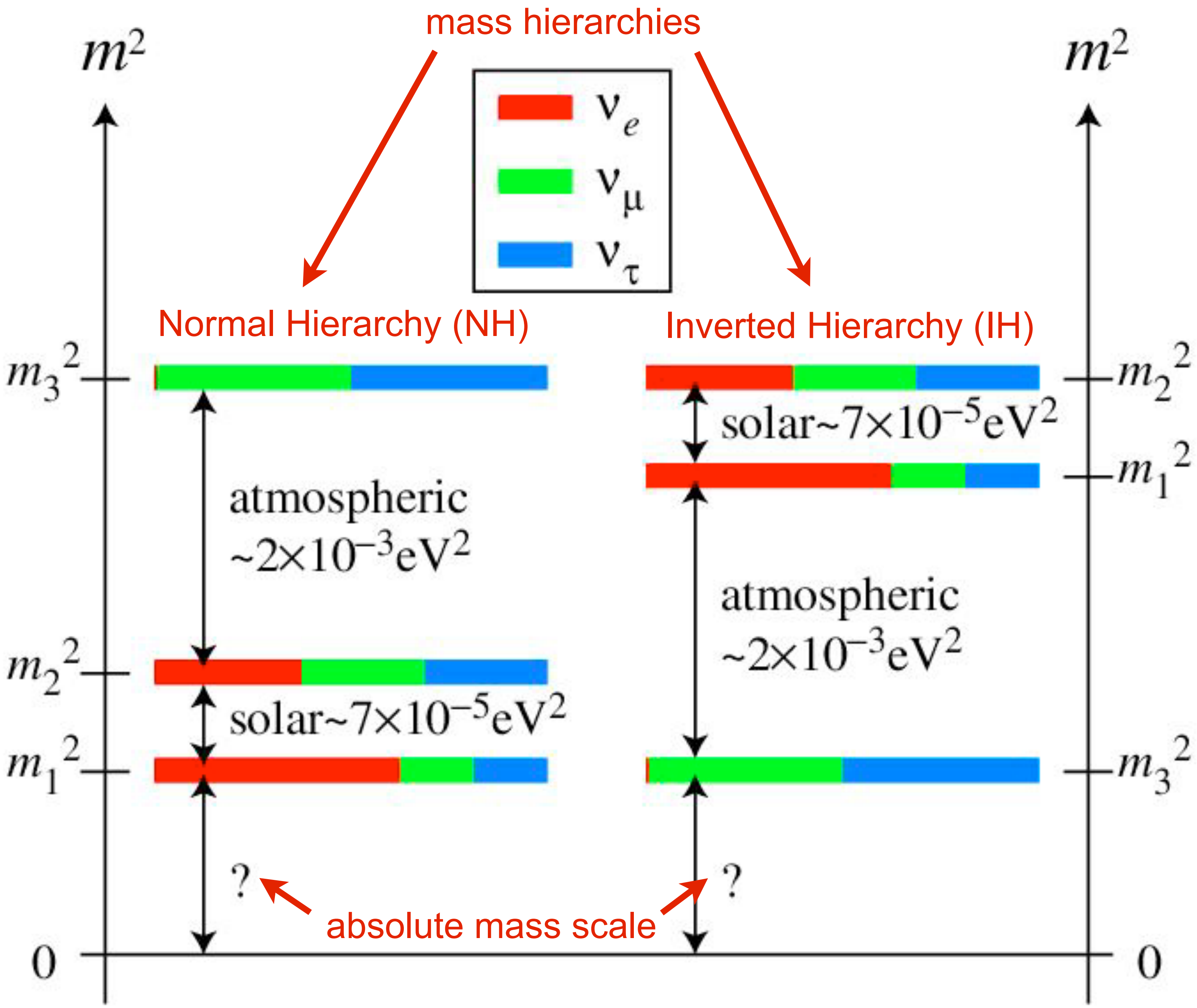
Measurements of neutrino parameters from:

- neutrino oscillations
- single beta decay
- cosmology
- neutrinoless double beta decay

Open questions

0ν-ββ can give an answer to three fundamental questions:

- Dirac or Majorana nature
- absolute mass scale:
  mass of the lightest ν
- hierarchy of masses

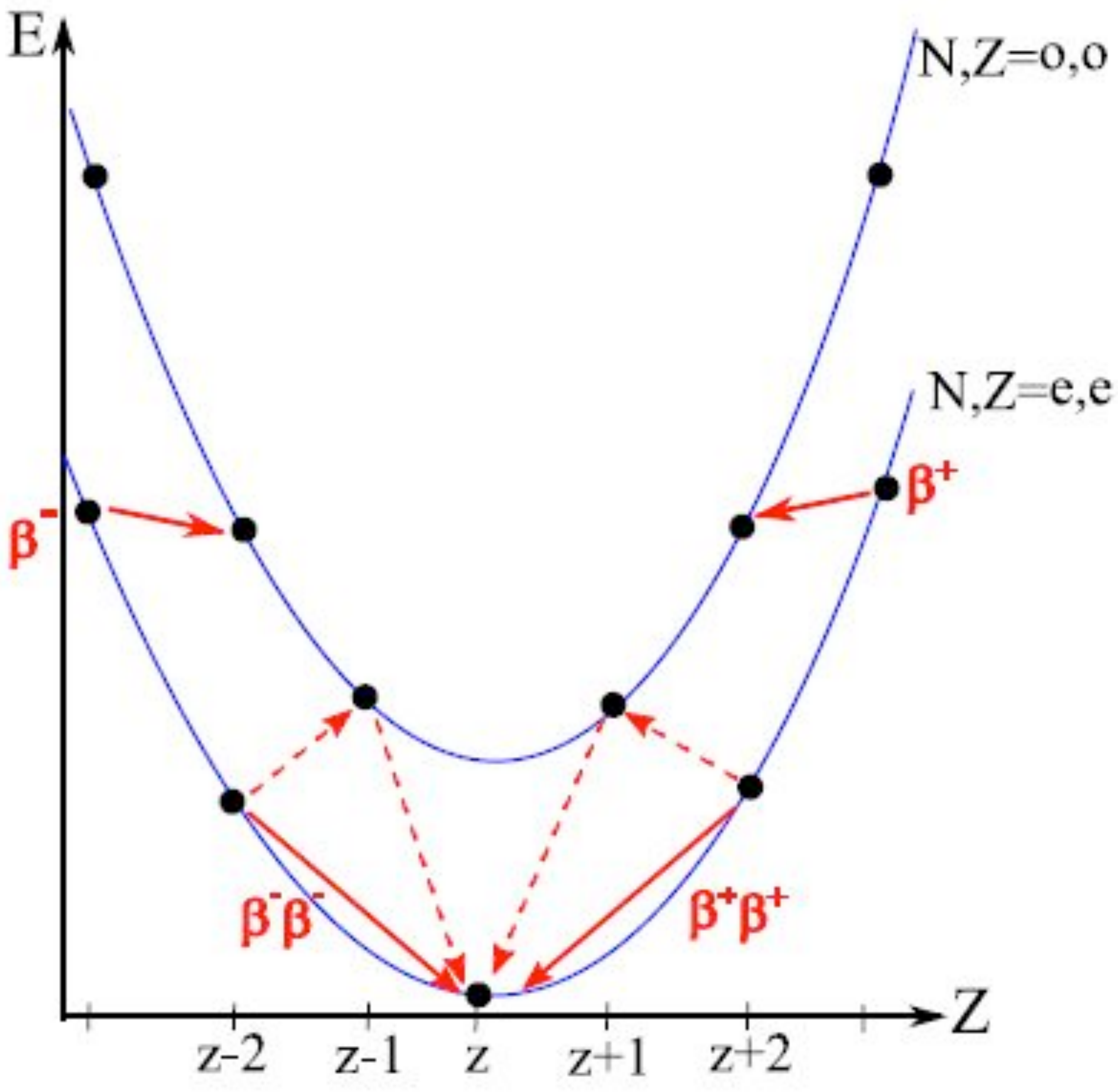


Oscillation experiments can determine the hierarchy but are blind to the other two questions

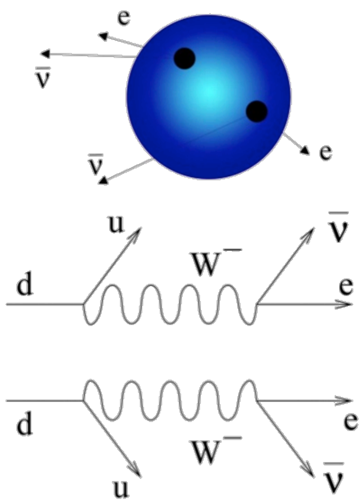
Double beta decay

Very rare nuclear decay (A,Z) → (A,Z+2) + $2e^-$ (+?)

Isotope	Q-value [keV]	Isotopic abundance
^{48}Ca	4272	0,19
^{76}Ge	2039	7,8
^{82}Se	2996	9,2
^{96}Zr	3350	2,8
^{100}Mo	3034	9,6
^{116}Cd	2814	7,6
^{130}Te	2527	33,4
^{136}Xe	2459	8,9
^{150}Nd	3371	5,6



Double beta decay

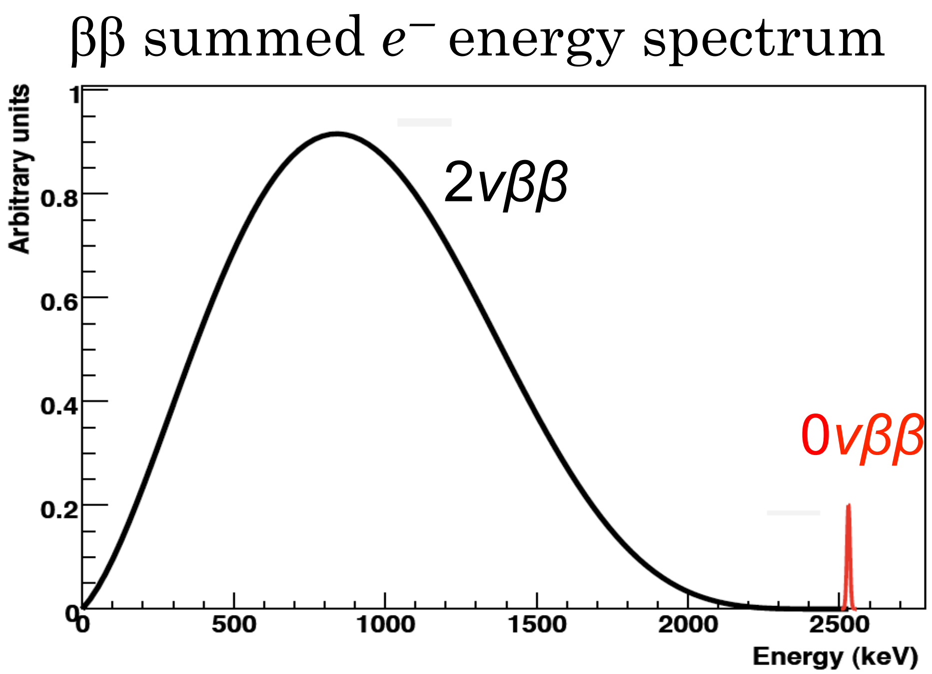


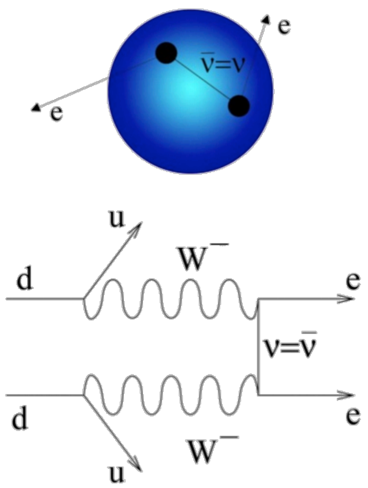
$$(A,Z)\rightarrow(A,Z+2)+2e^-+2\overline{\nu}$$

2ν-DBD

2nd order process allowed in the SM

observed in several nuclei with $\tau^{2\nu} \sim 10^{19}\text{-}10^{21}$ y


ββ summed e^- energy spectrum



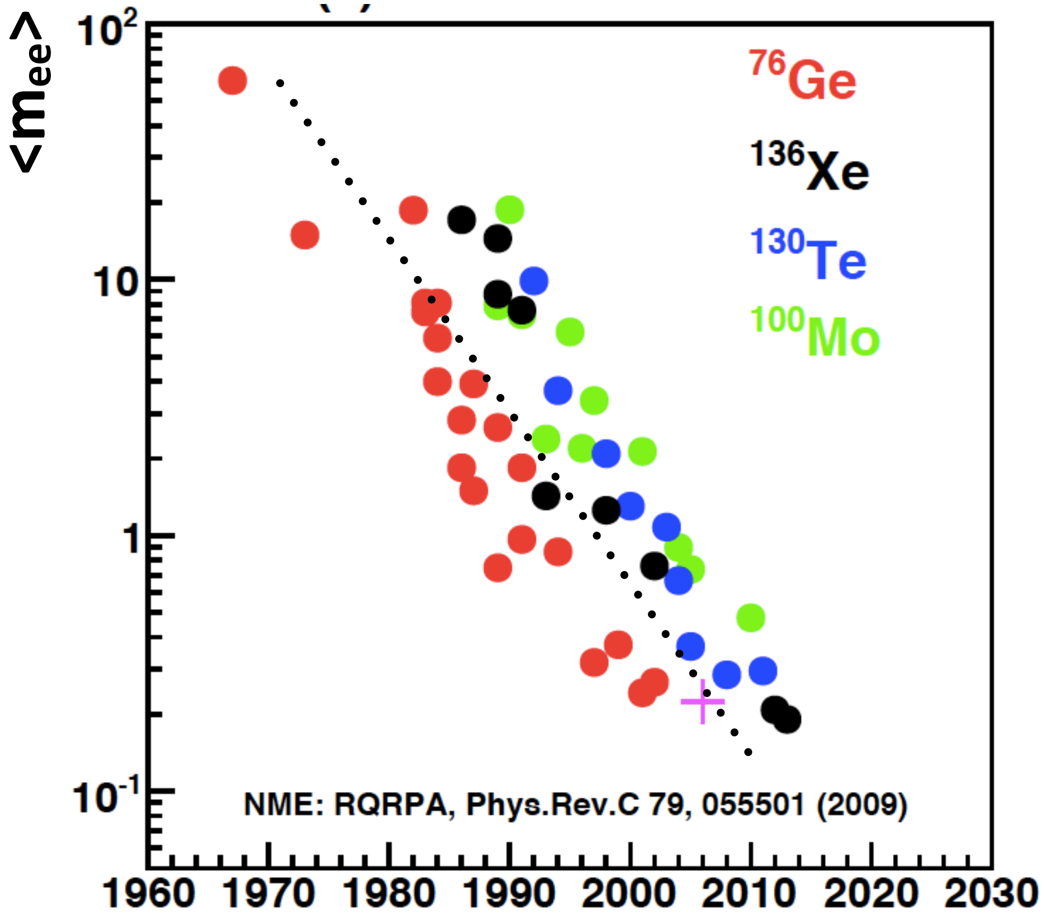
$$(A,Z)\rightarrow(A,Z+2)+2e^-$$

0ν-DBD (implies physics beyond SM)

lepton number violating process

$\tau^{0\nu} > 10^{24}\text{-}10^{25}$ y

exists if neutrino is a Majorana particle and $m_\nu \neq 0$



NME: RQRPA, Phys.Rev.C 79, 055501 (2009)

A long history of 0ν-ββ experiments

An order of magnitude on the effective Majorana mass every 15 years?

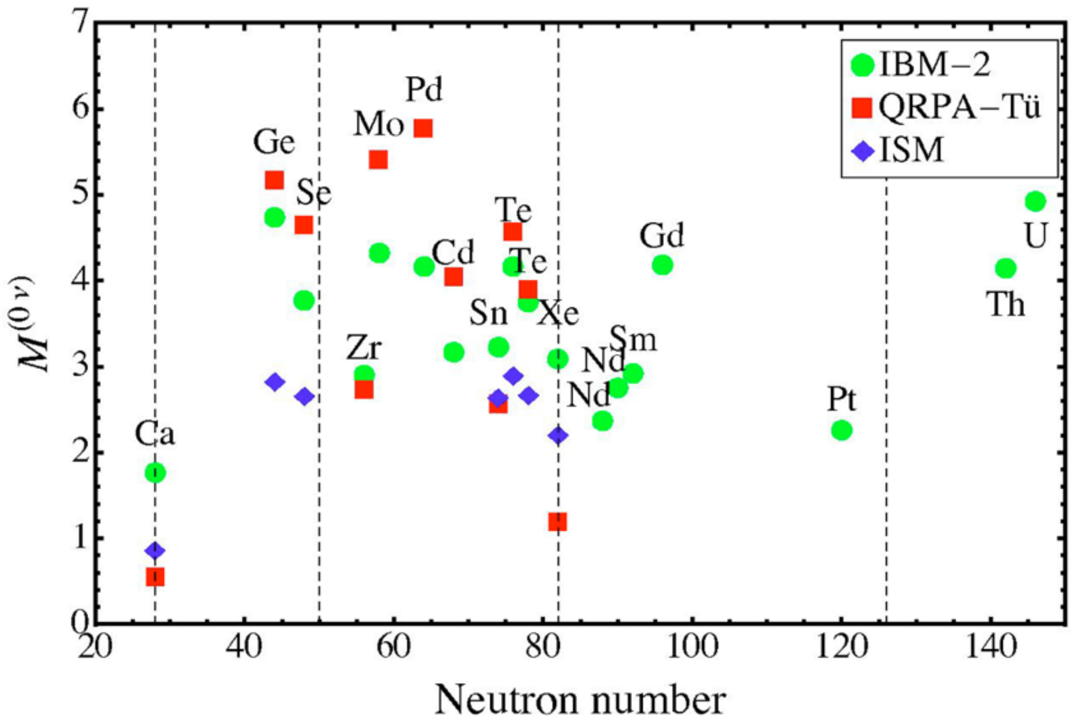
0ν-ββ and Majorana mass

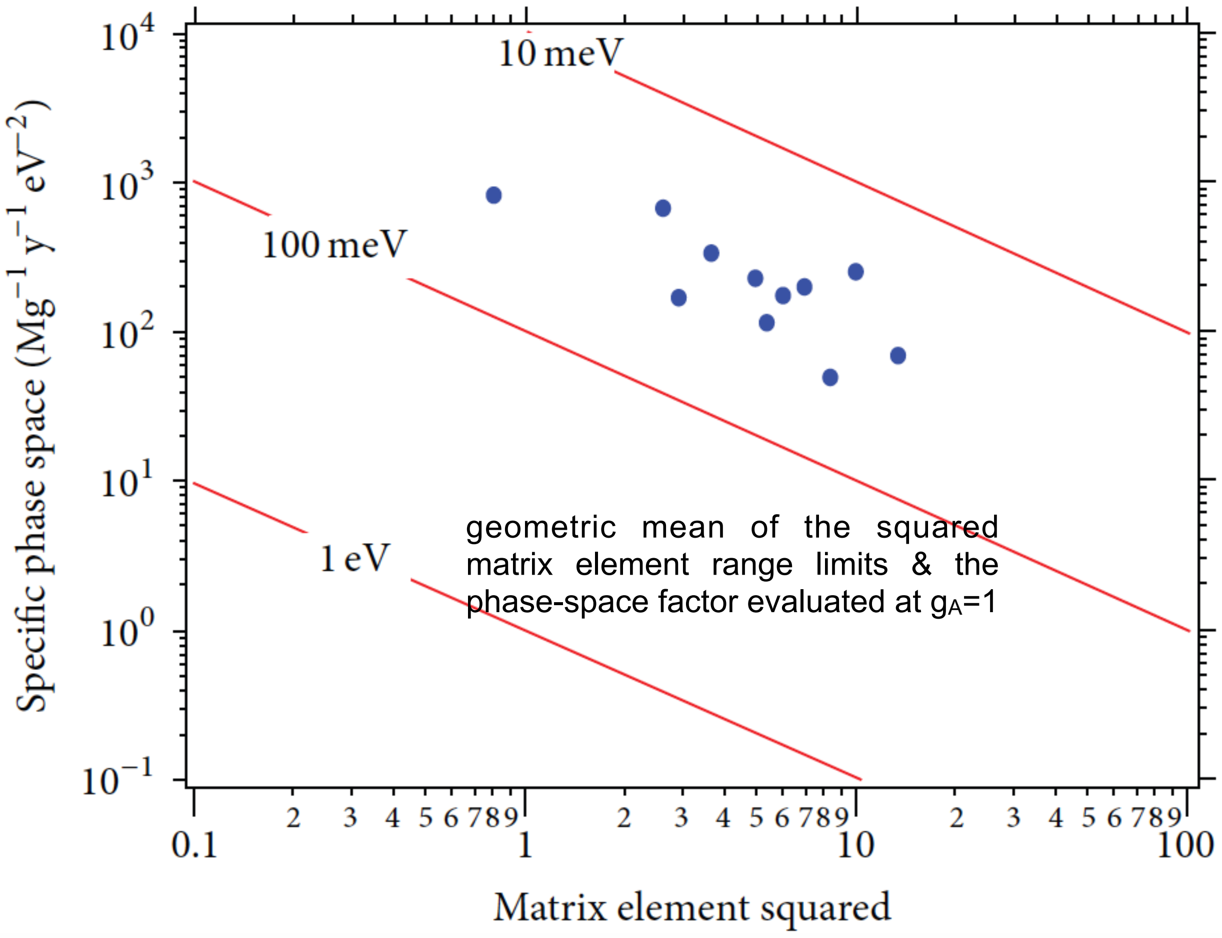
$$\underbrace{[T^{0\nu}_{1/2}]^{-1}}_{\text{0νββ decay rate}} = \underbrace{G_{0\nu}}_{\text{Phase space factor}} \underbrace{g_A^4}_{\text{Axial vector coupling}} \underbrace{|M_{0\nu}|^2}_{\text{Nuclear matrix element}} \underbrace{\langle m_{\beta\beta}\rangle^2}_{\text{Effective Majorana mass}}$$

$$\langle m_{\beta\beta}\rangle = \sum_k \underbrace{U_{ek}^2}_{\text{NEUTRINO MIXING MATRIX}} \overbrace{m_k}^{\text{NEUTRINO MASS EIGENVALUES}} = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

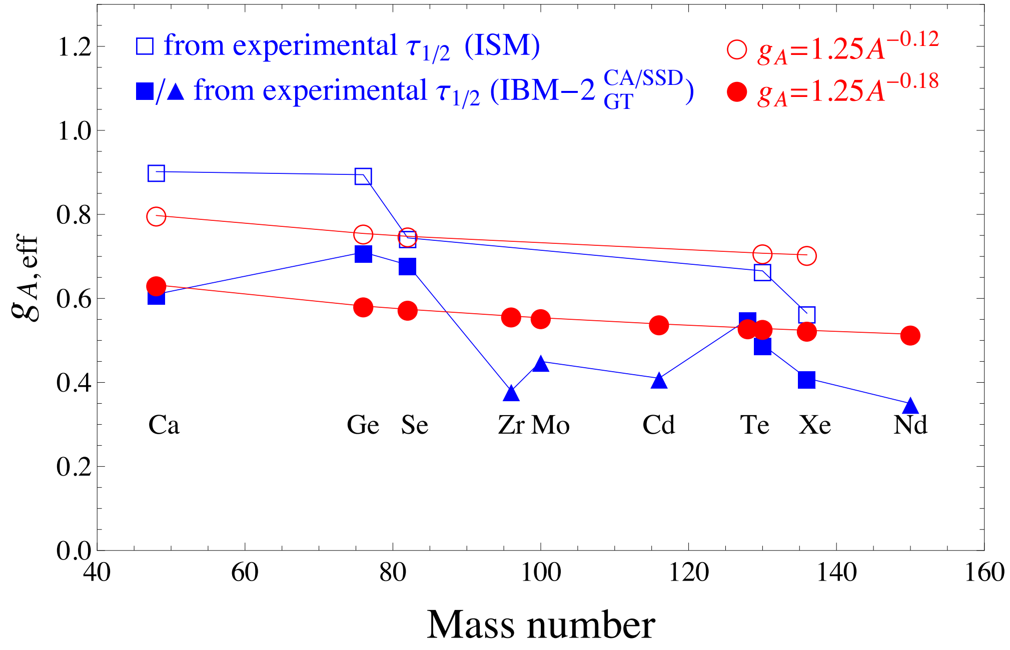
Is there a preferred isotope?

- Nuclear matrix elements calculations are rapidly improving and today the differences between different methods (IBM, QRPA, ISM) are much smaller than in the past
- Uncertainty on g_A plays a relevant role
  factor 2 in g_A is a factor 16 in decay rate
- inverse correlation observed between phase space and square of the nuclear matrix element





geometric mean of the squared matrix element range limits & the phase-space factor evaluated at g_A=1

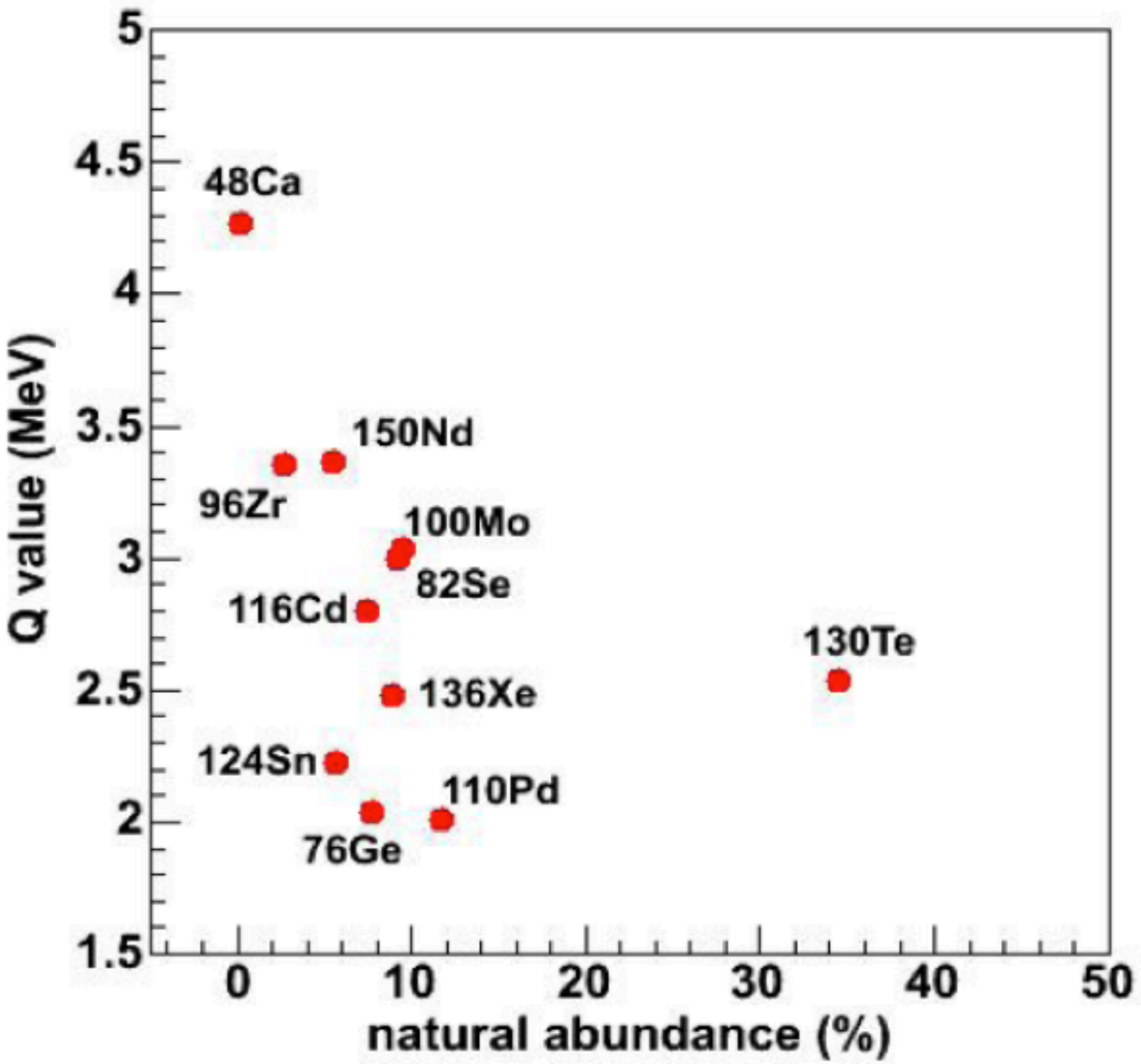


Isotope choice

In many cases driven by the detector characteristics.

- ^{76}Ge with Germanium diodes
- ^{136}Xe with Xenon TPCs
- bolometers and scintillators have multiple choices

- Isotopic abundance as high as possible
  - money issue
- Q-value as high as possible
  - lower environmental background
- 2v-DBD half-life as high as possible
  - energy resolution



Sensitivity

Half-life corresponding to the minimum detectable number of events over background at a given confidence level

$$S_{0\nu} = ln(2) N_A \frac{\eta \cdot \epsilon}{W} \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

$$S_{0\nu} = ln(2) N_A \frac{\eta \cdot \epsilon}{W} M \cdot T$$

finite background: $M \cdot T \cdot B \cdot \Delta E > 1$

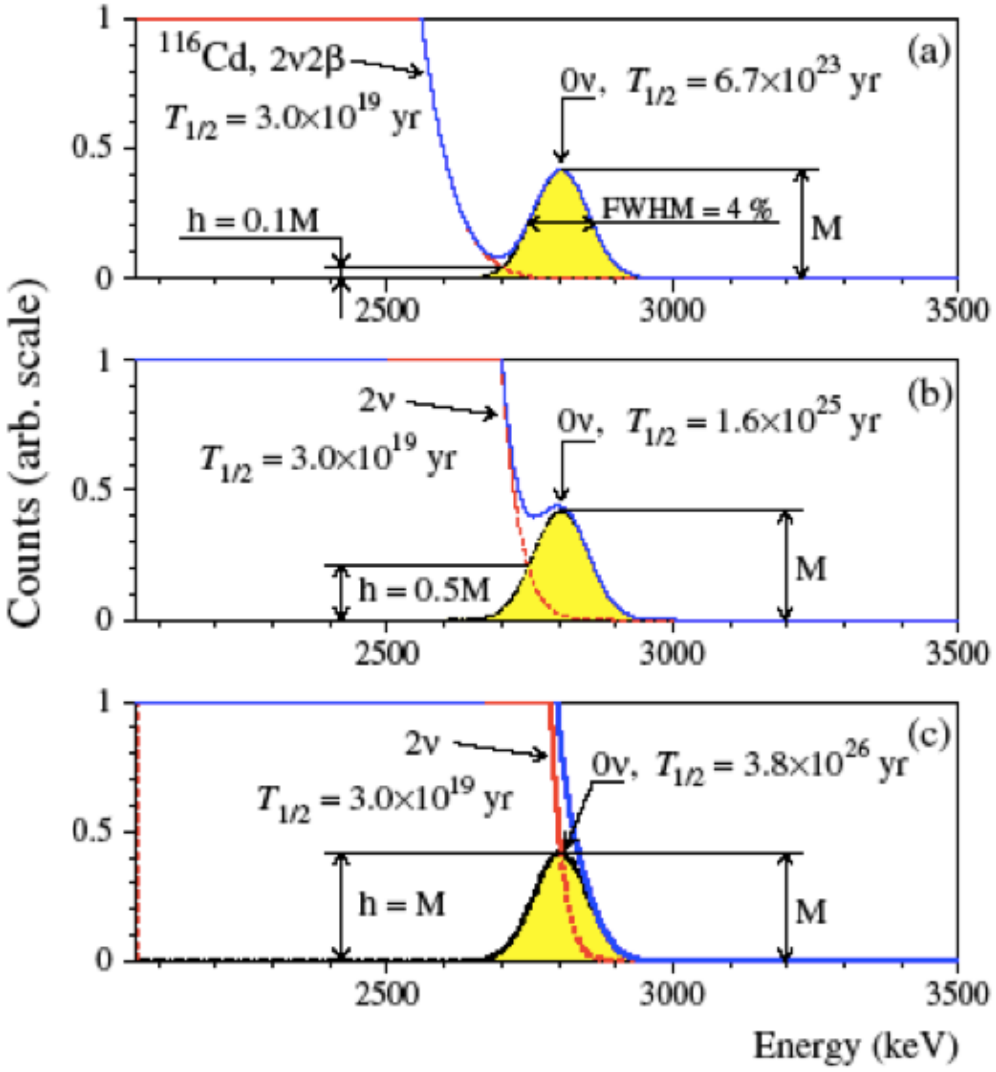
zero background: $M \cdot T \cdot B \cdot \Delta E \lesssim 1$

M: active detector mass [kg]
T: measurement life time [anni]
B: background in the ROI [counts keV^{-1} kg^{-1} y^{-1}]
W: molecular weight

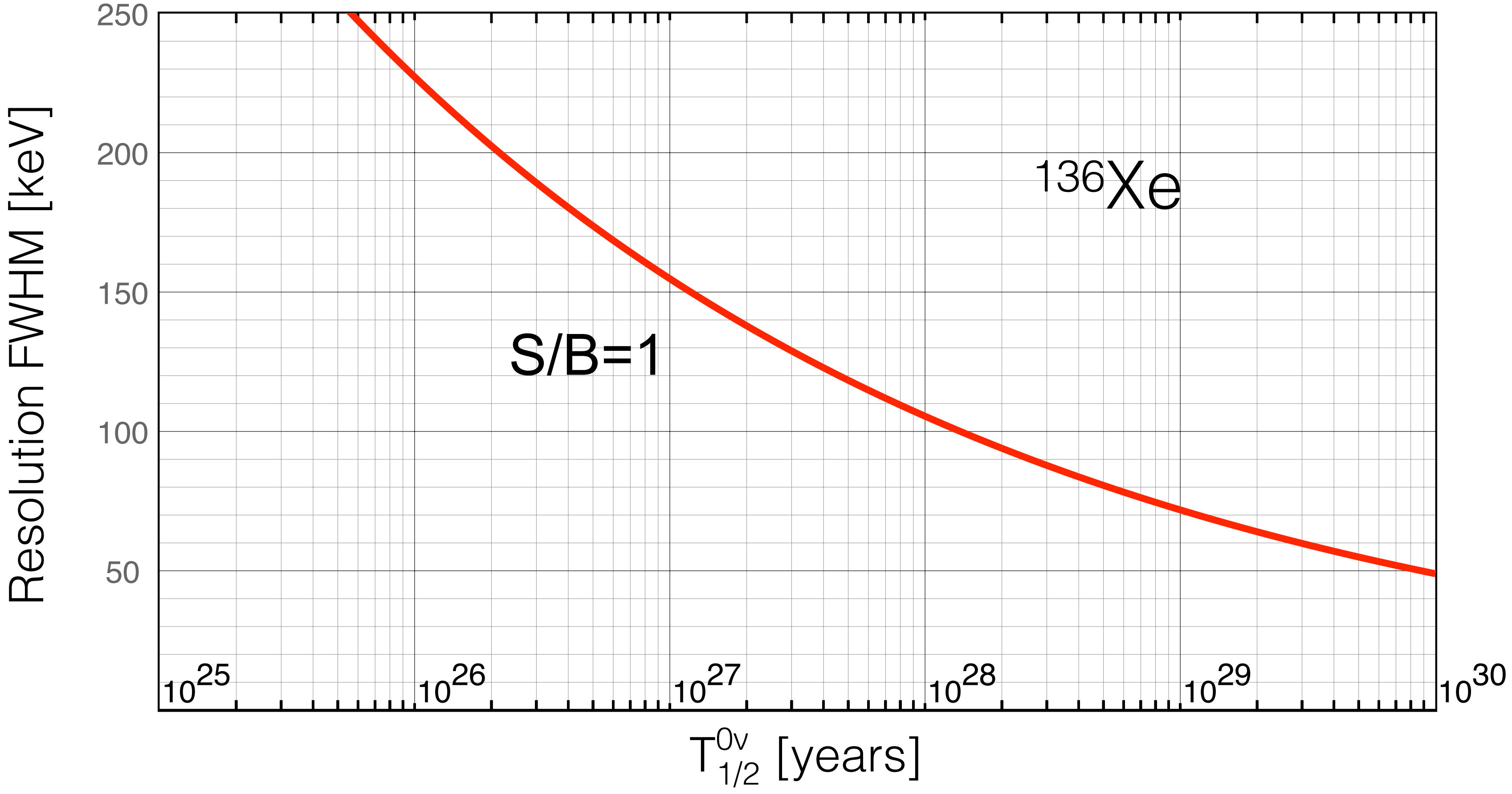
N_A: Avogadro number
η: isotopic abundance
ε: detector efficiency
ΔE: FWHM energy resolution @ Q-value

Irreducible background from 2ν-ββ

- The irreducible background induced by the 2ν-ββ could be mitigated just by the energy resolution
- The effect can be partially attenuated with an asymmetric ROI (but losing efficiency)



Zdesenko, Danevich, Tretyak, J. Phys. G 30 (2004) 971

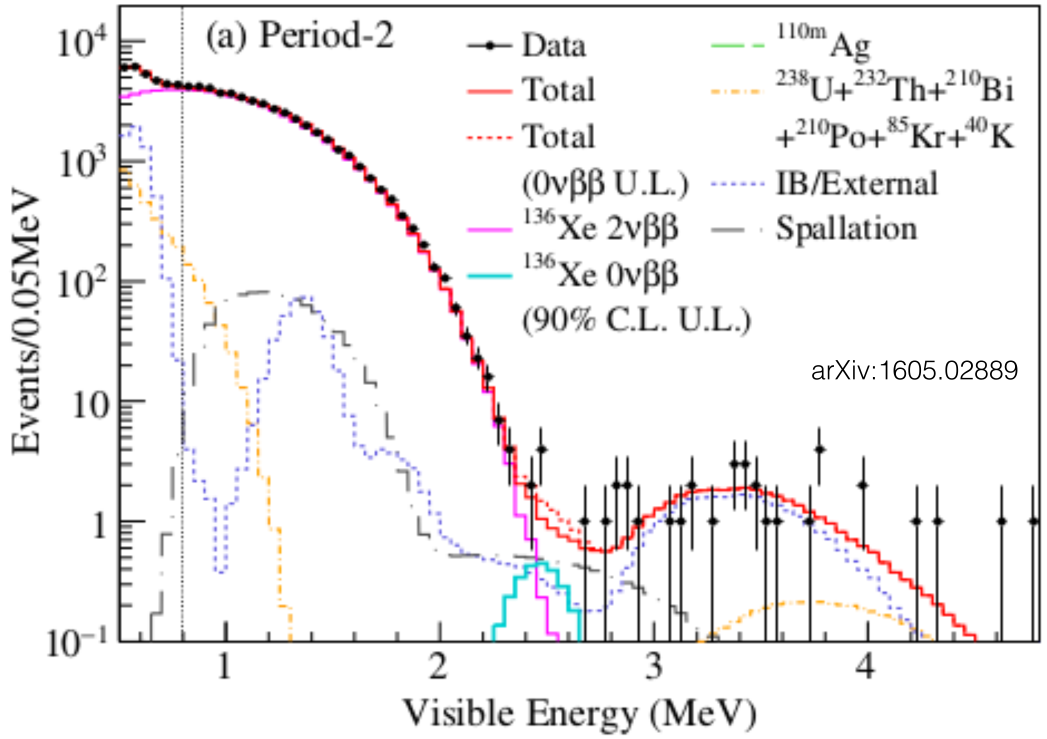


$$\frac{S}{B} = \frac{m_e}{7Q\delta^6}\frac{\Gamma_{0\nu}}{\Gamma_{2\nu}} = \frac{m_e}{7Q\delta^6}\frac{T^{2\nu}_{1/2}}{T^{0\nu}_{1/2}}$$

Key ingredients

- Number of nuclei of the chosen isotope
  - Detector mass
  - Isotopic abundance -> enrichment -> money
- Background
  - radio purity and shieldings
  - discrimination capability
- Energy resolution
  - detector dependent
  - easier identification of the background contributions
  - less probability of accidental superposition with environmental radioactivity peaks
    (e.g. 2448 keV of ^{214}Bi at ~10 keV from ^{136}Xe Q-value
    2505 keV sum of the ^{60}Co peaks at ~20 keV from ^{130}Te Q-value)
  - mitigate the background induced by 2v-DBD

Kamland-zen



arXiv:1605.02889

- Double beta decay experiments: limits vs discovery
  - Solid state detectors: have better resolution but is more difficult to reach very low background and increase mass
    - ➡ discovery potential
  - Liquid scintillators and TPCs have poor energy resolution but its easier to reach large masses and they can be purified
    - ➡ in case of a positive signal difficult to disentangle from possible background sources

LNGS has a leadership role in “discovery” experiments

Neutrinoless ββ decay @ LNGS

A long history in 0νββ search

- MiDBD (^{130}Te)
- Heidelberg-Moscow (^{76}Ge)
- Cuoricino (^{130}Te)
- GERDA-I (^{76}Ge)
- CUORE-0 (^{130}Te)

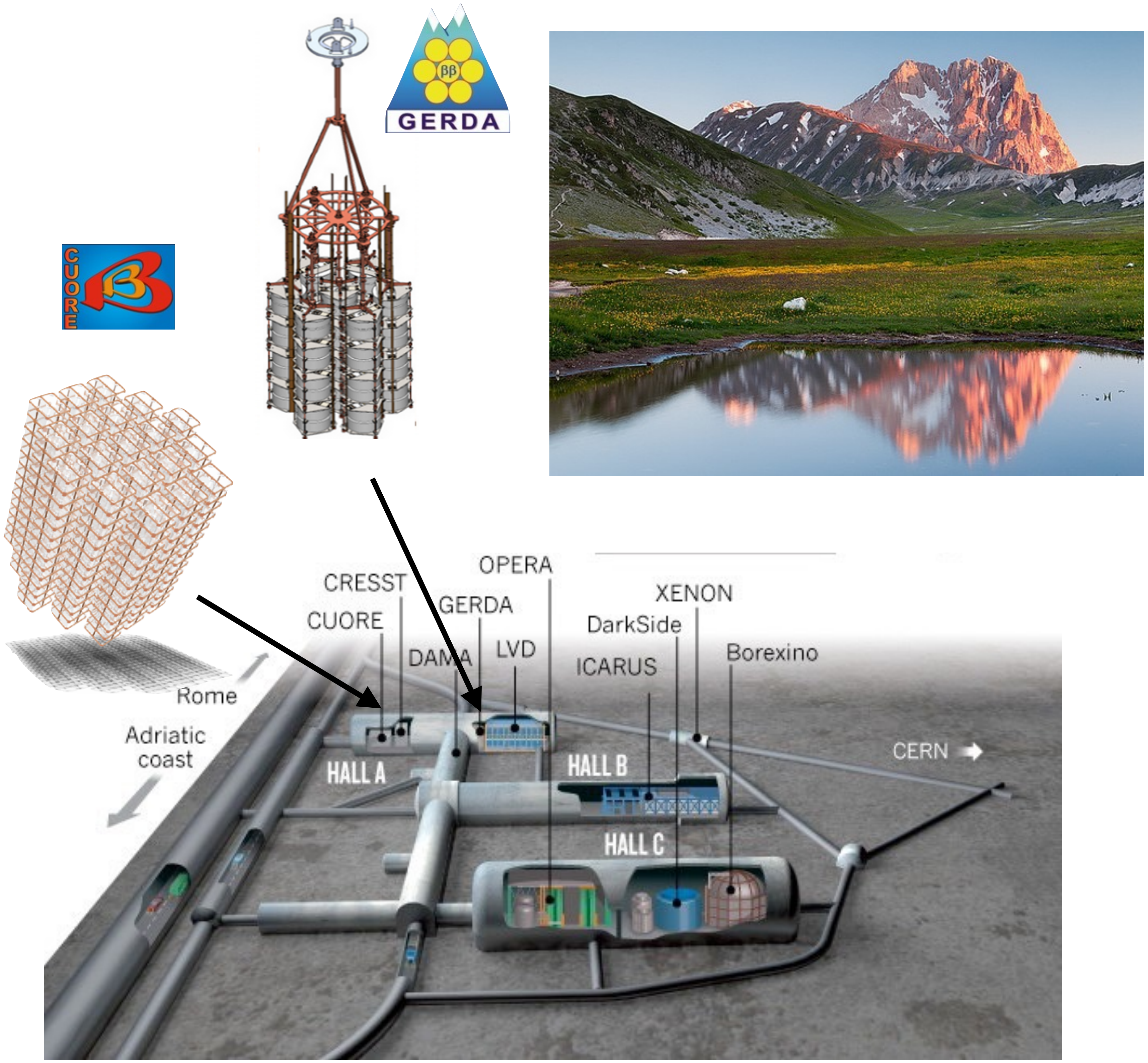
R&D projects

- Cobra (^{116}Cd)
- CUPID-0/LUCIFER (^{82}Se)
- DAMA R&D (^{116}Cd)

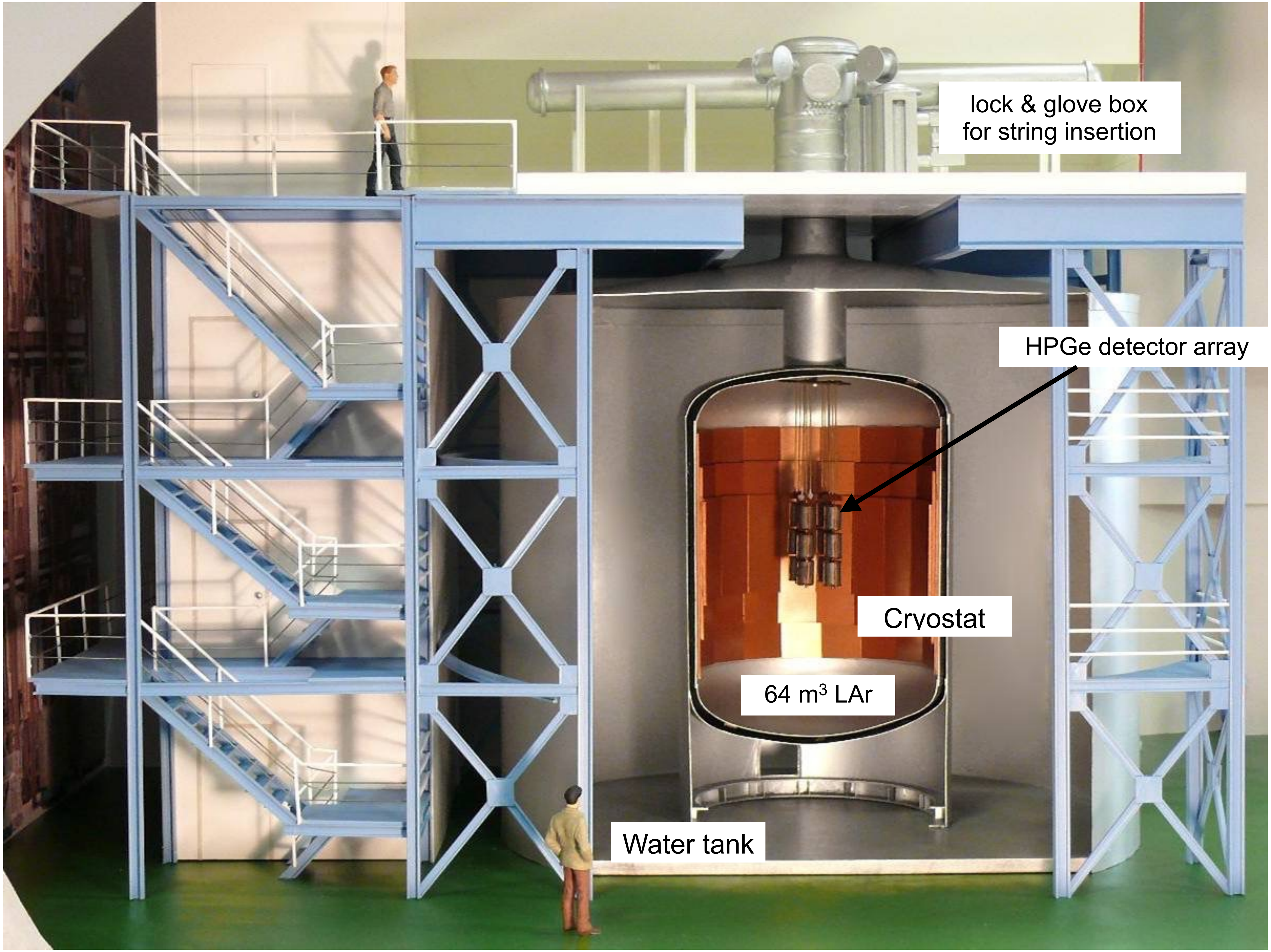
important role in the near future

- GERDA-II (^{76}Ge)
- CUORE (^{130}Te)

- ~3600 m.w.e. deep
- μ_S: ~3x10^{-8}/(s cm^2)
- γ_S: ~0.73/(s cm^2)
- neutrons: 4x10^{-6} n/(s cm^2)

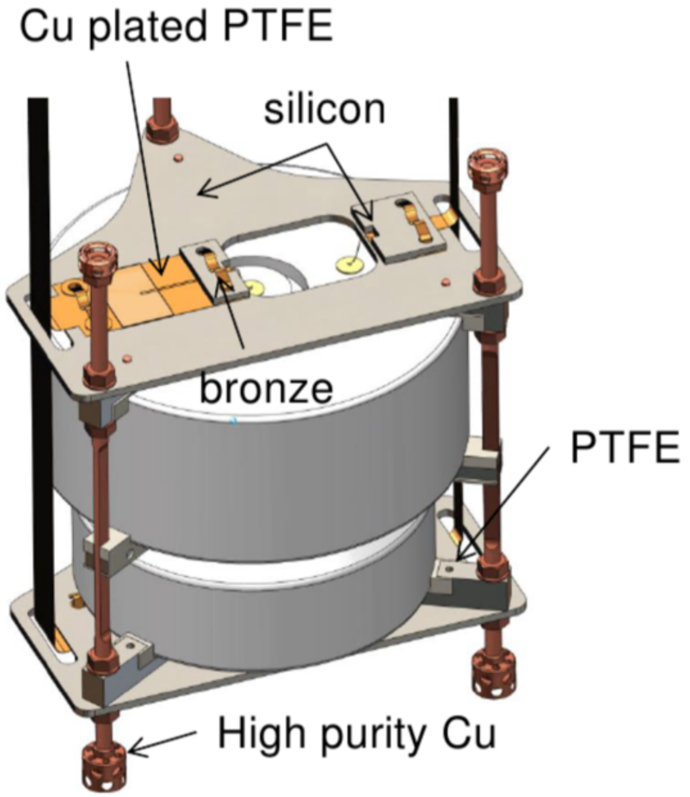


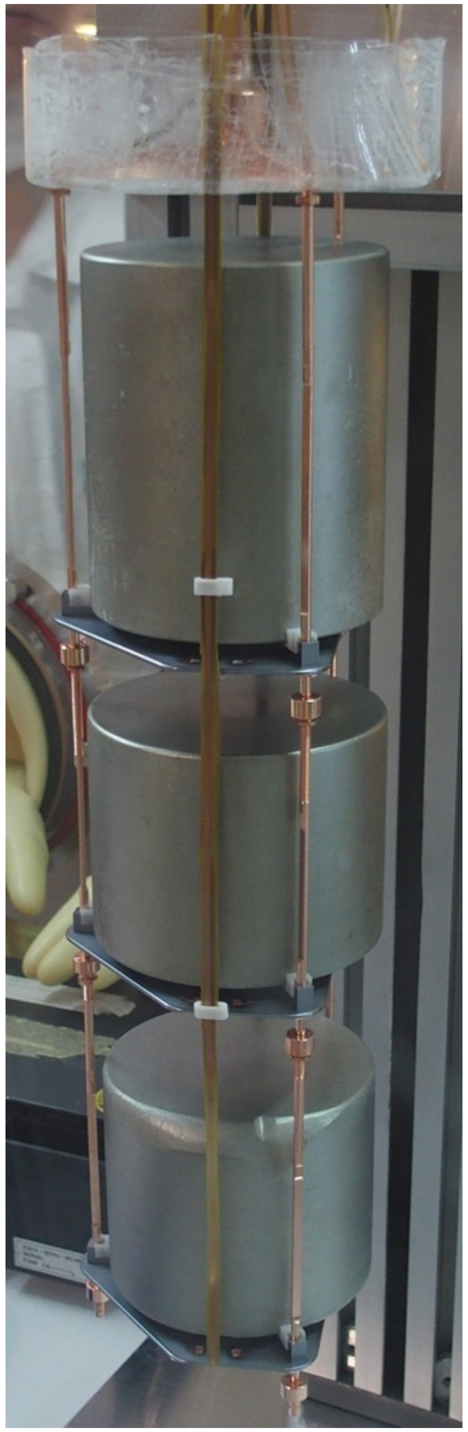
GERmanium Detector Array



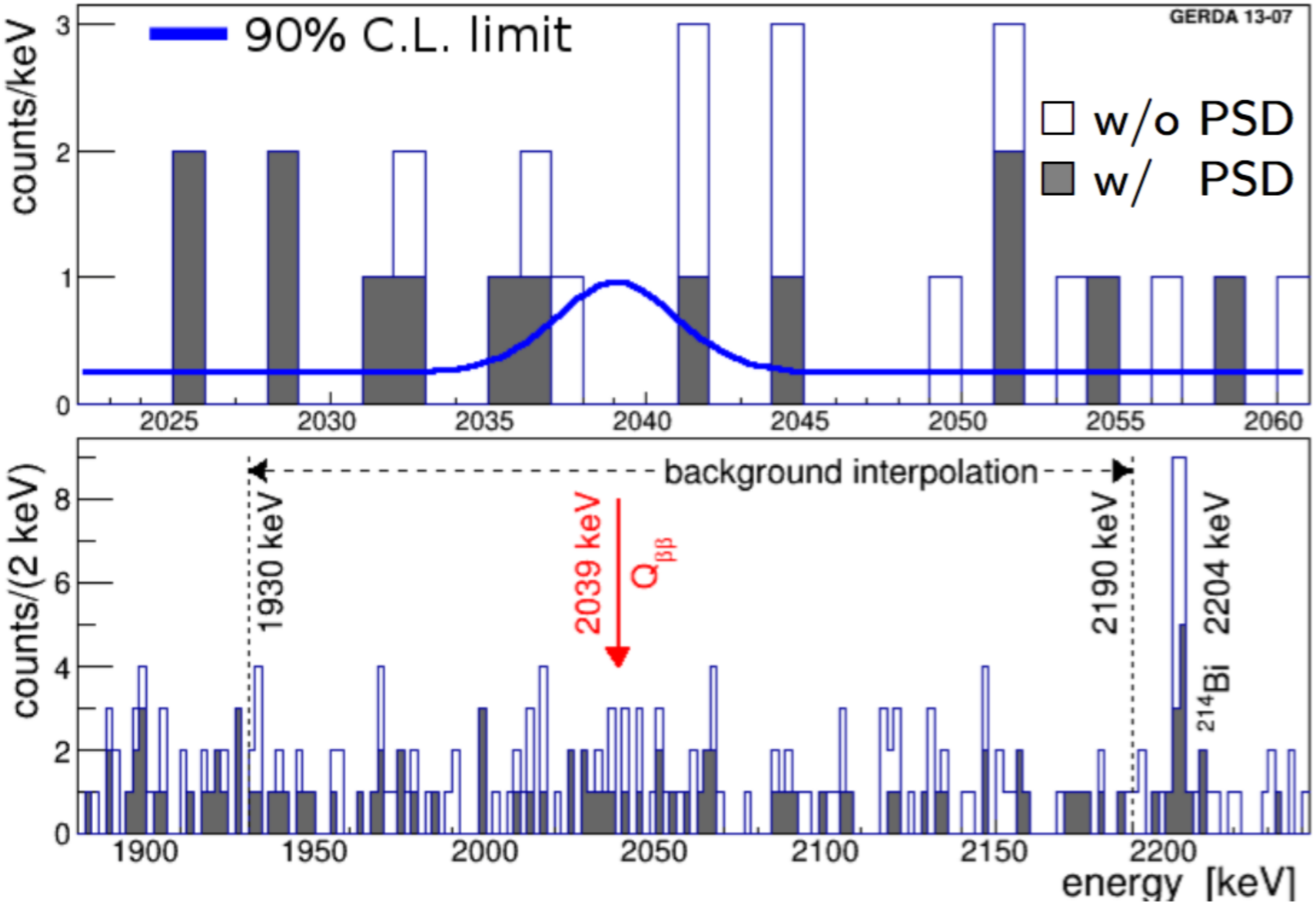
GERDA

- High purity semiconductor
- Enrichment: ~ 86% of ^{76}Ge
- $Q_{\beta\beta}$ value 2039 keV
- Energy resolution @ $Q_{\beta\beta}$ ~ 0.2% (FWHM)
- High detection efficiency
- Modular
- Point-like energy deposition (PSD)





GERDA Phase I results



- Exposure 21.6 kg · yr
- Blind analysis
- Detection efficiency:
  - 62% for Coax
  - 66% for BEGe
- Sensitivity $2.4 \cdot 10^{25}$ yr
- No counts in 2039 keV$\pm 1\sigma$

$T_{1/2} > 2.1\times10^{25}$ yr

$< m_{\beta\beta} > < 0.2$–0.4 eV (90% C.L.)

GERDA Phase II

Goals:

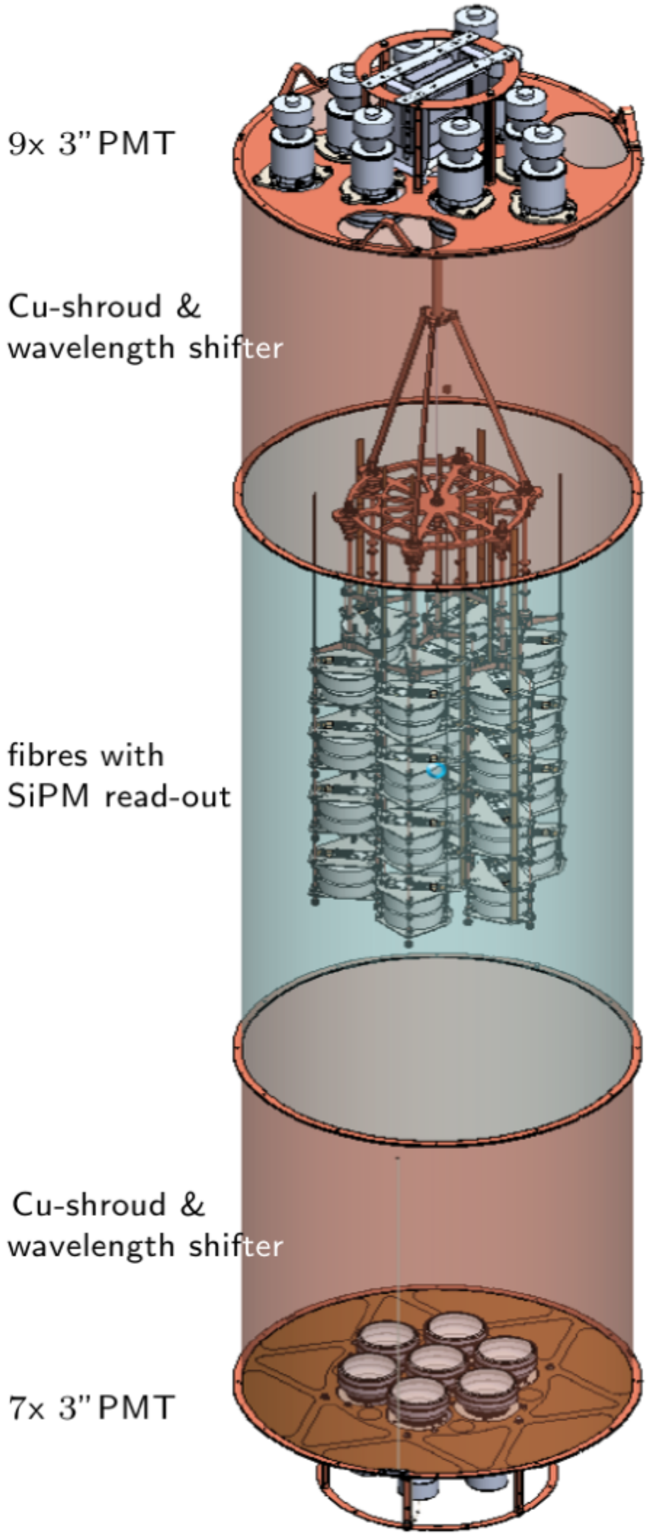
- Sensitivity above 1 · 10^{26} yr
- Exposure ~ 100 kg · yr
- Background index 10^{-3} c/(keV·kg·yr)

What's new?

- 30 custom BEGe detectors (~ 20 kg)
- energy resolution ~ 3keV FWHM @ 2MeV
- pulse shape discrimination of bulk SSE against surface events (α&β) and MSE

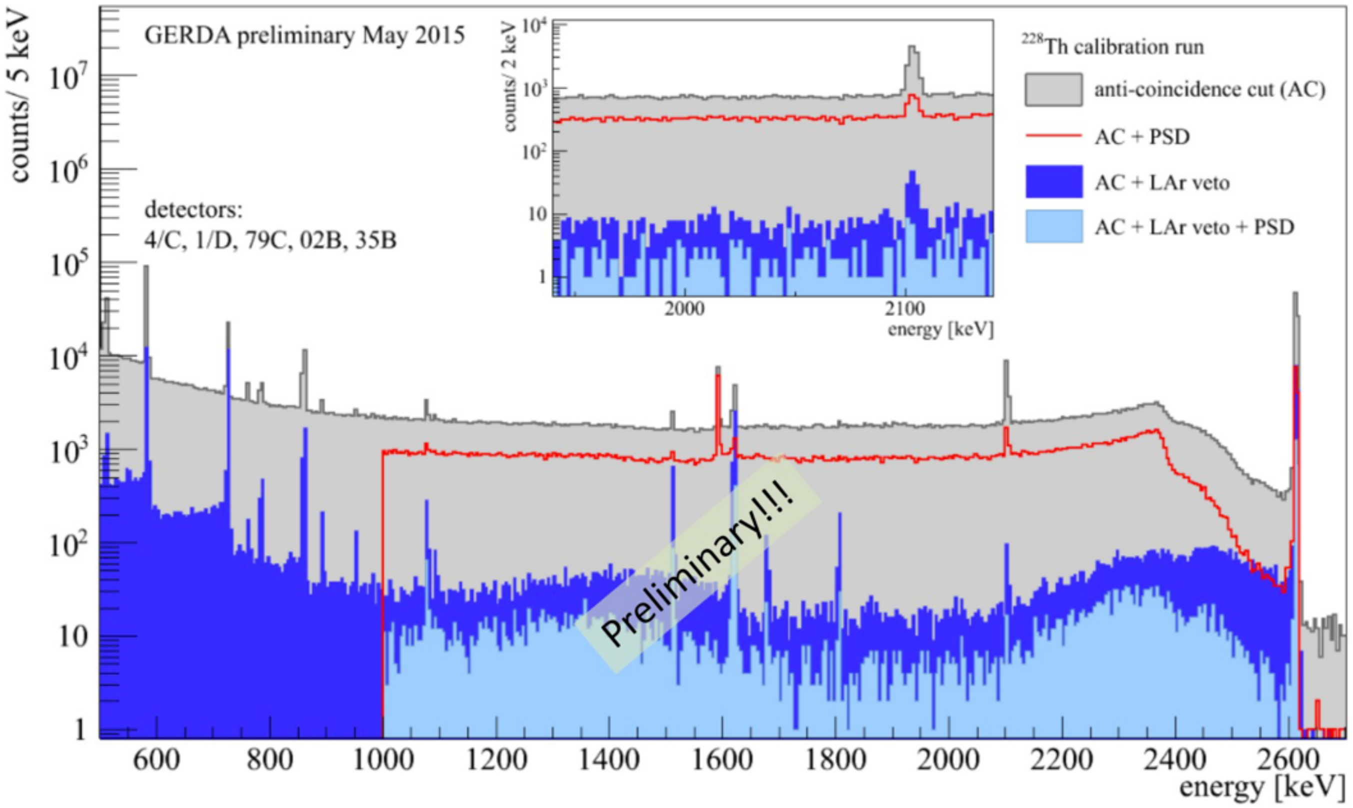
Background veto

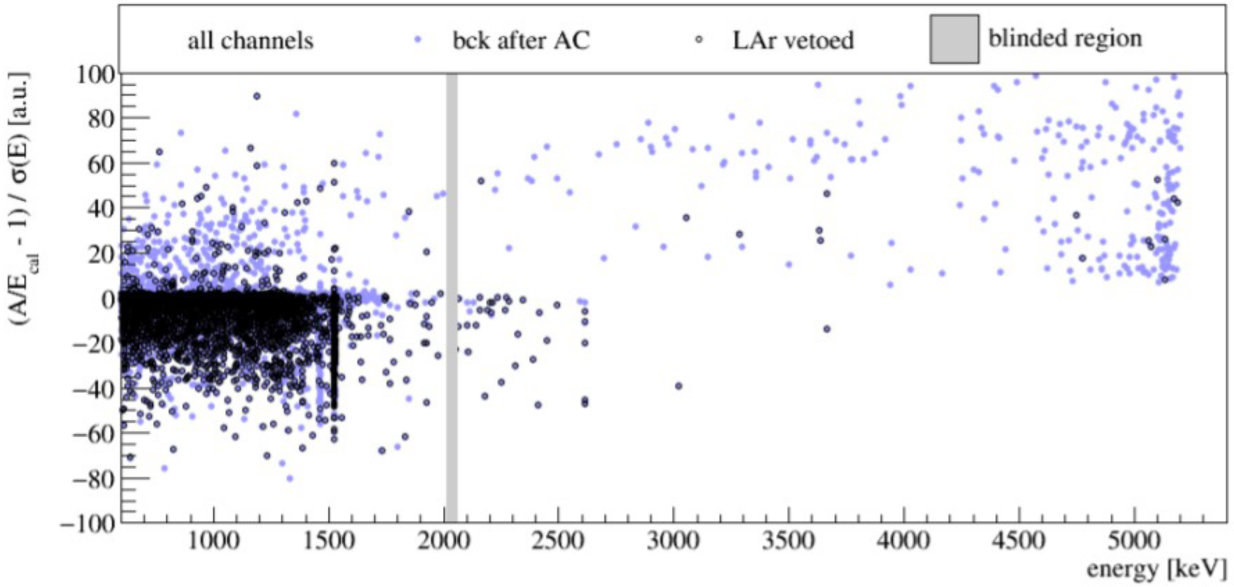
- LAr scintillating read–out
- better anti-coincidence

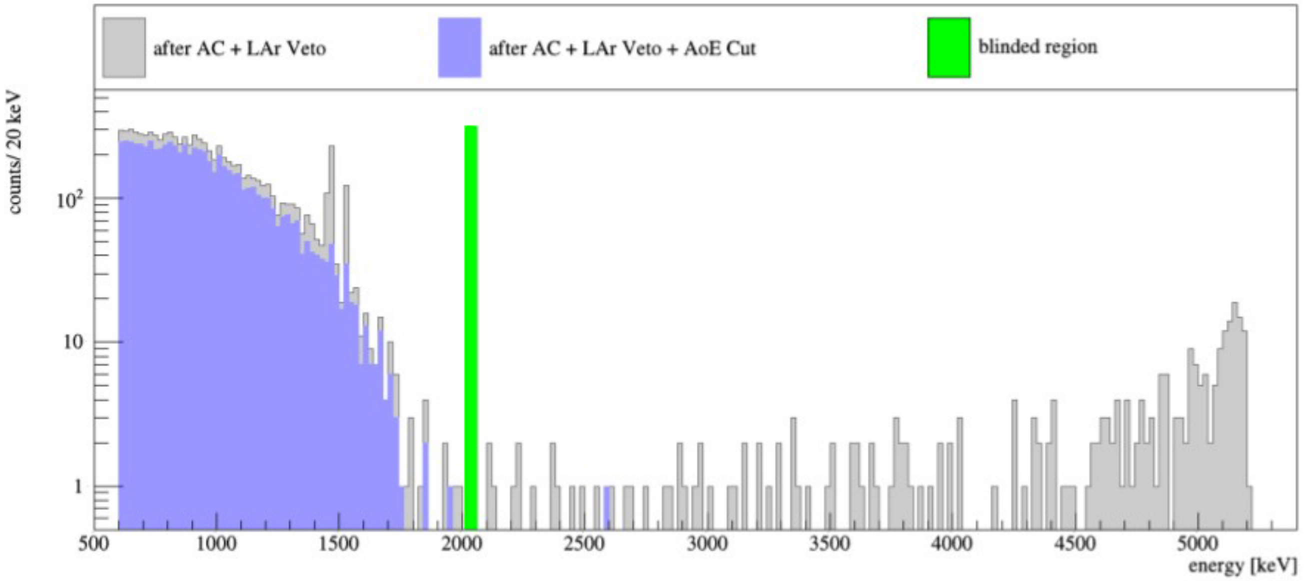


Background discrimination

- Anti-coincidence
- LAr veto
- PSD cuts

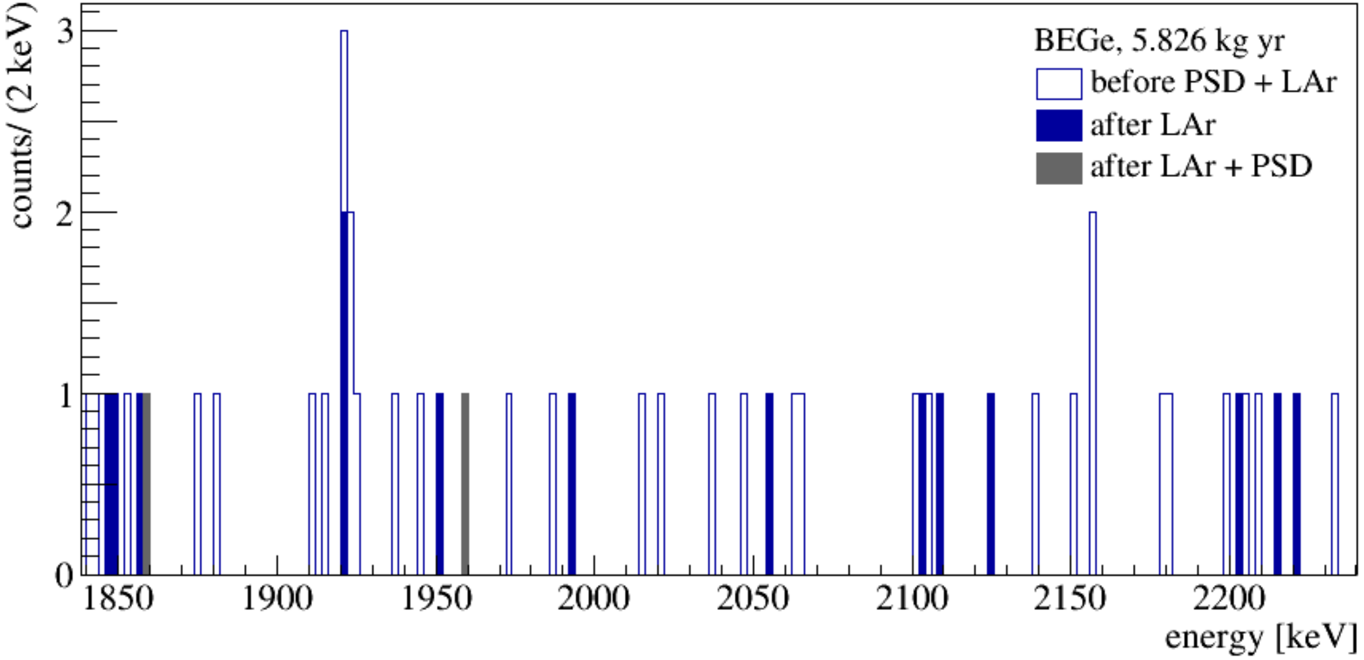




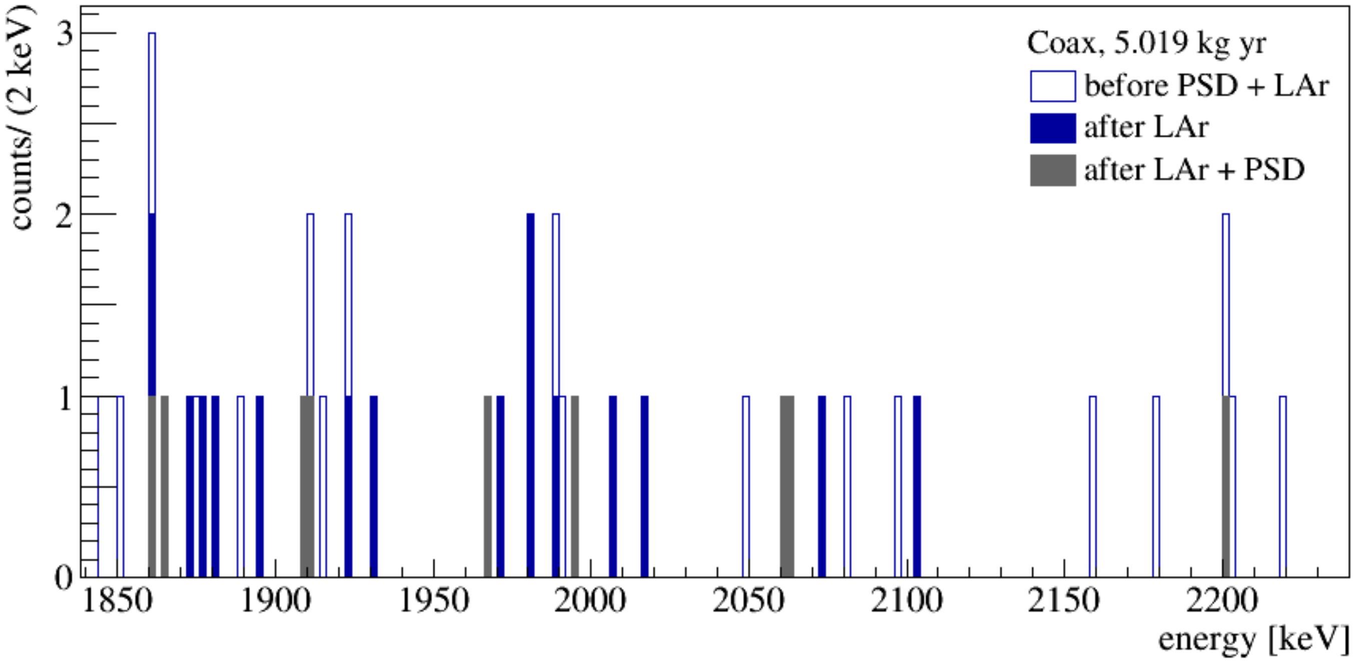


GERDA Phase II preliminary results

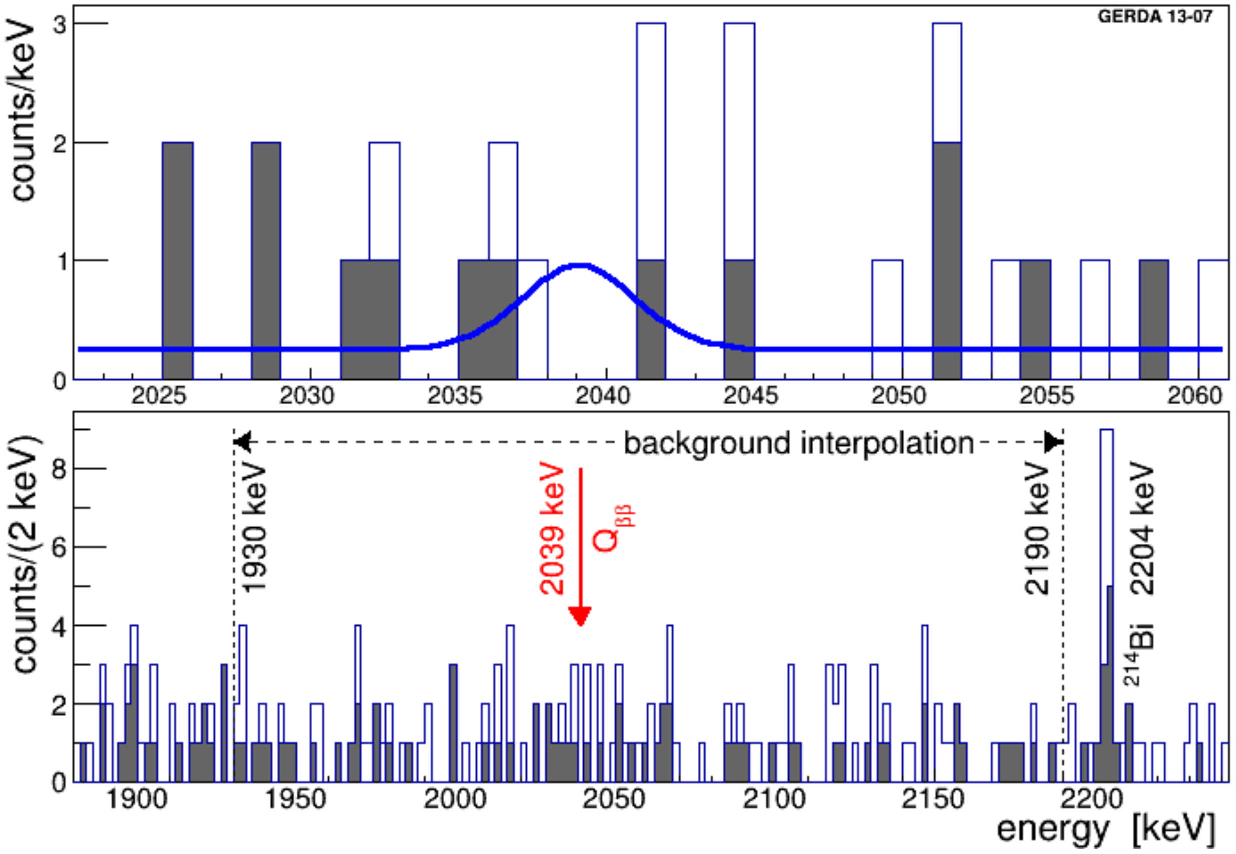
Phase II BEGe: 5.8 kg yr



Phase II Coax: 5.0 kg yr



Phase I: 21.7 kg yr



Background (BEGe) $0.7^{+1.2}_{-0.5} \times 10^{-3}$ c/keV/kg/yr

$T_{1/2}$ >5.3 10^{25} yr (90% CL, frequentist)

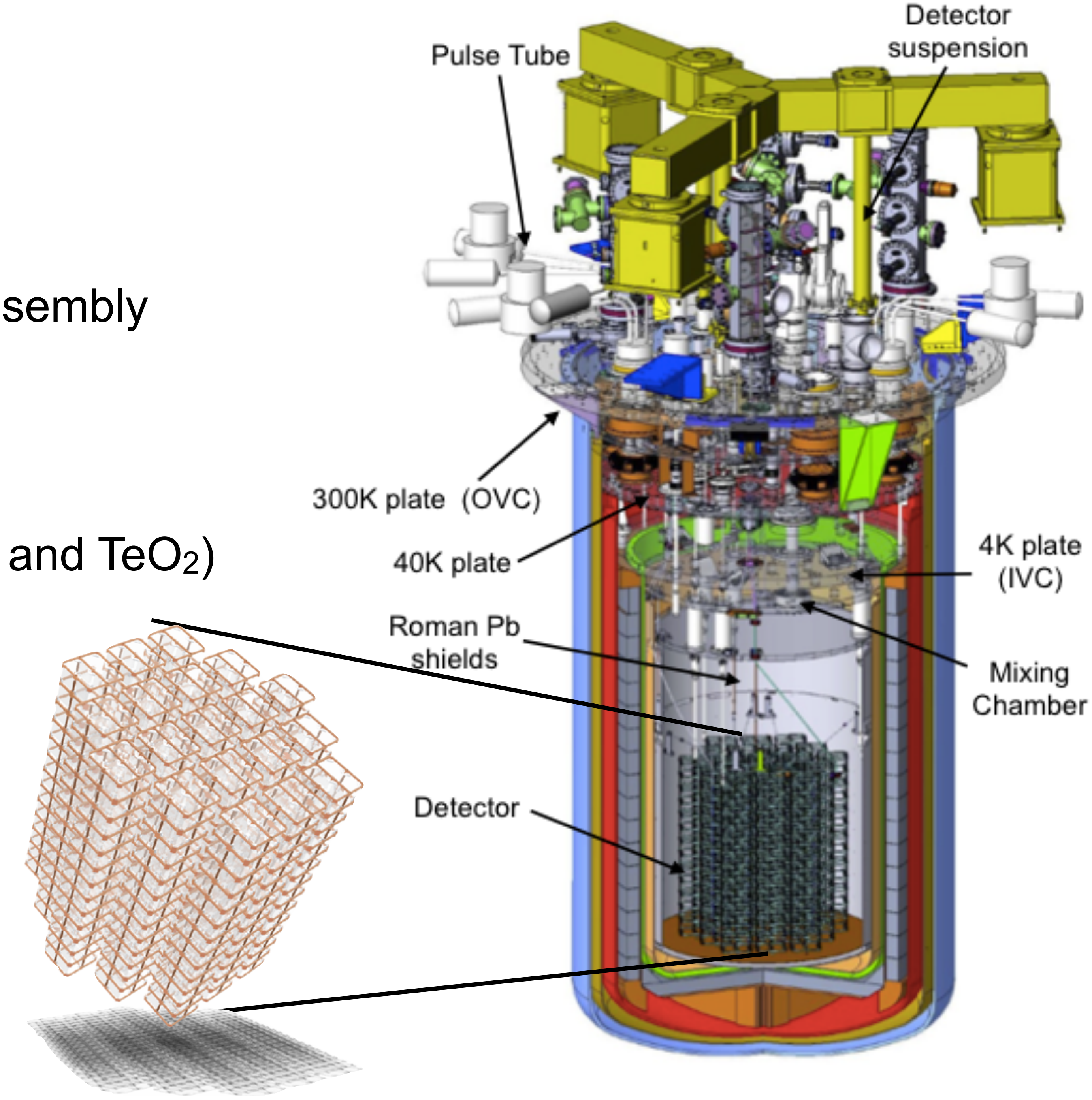
$T_{1/2}$ >3.5 10^{25} yr (90% credible, Bayesian)

This result suggests future Ge experiments with 200 kg and beyond

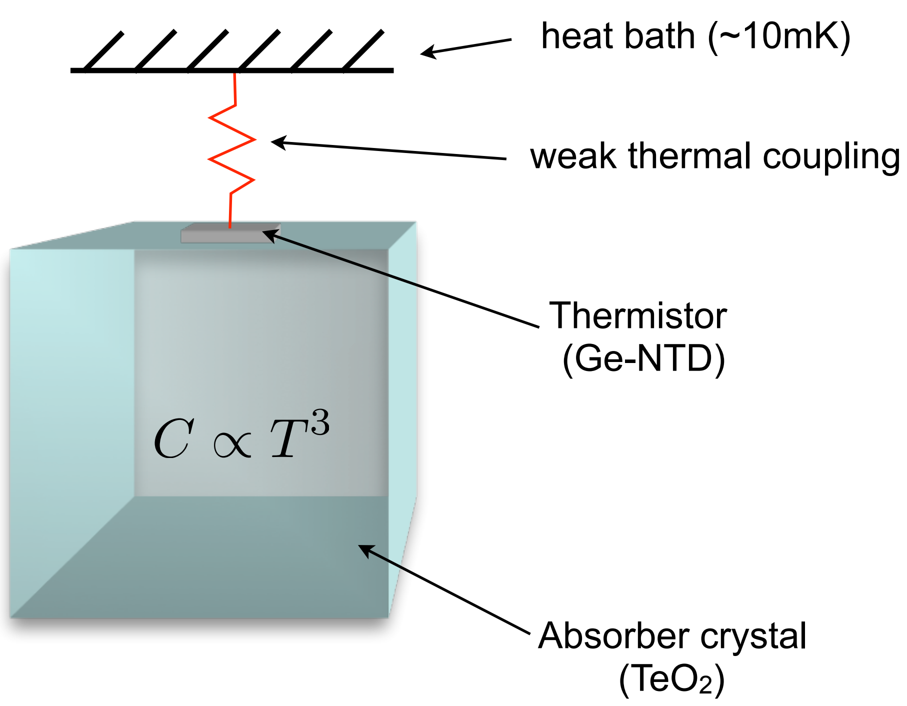
The CUORE challenge

Operate a huge thermal detector array in a extremely low radioactivity and low vibrations environment

- Closely packed array of 988 TeO_2 crystals (19 towers of 52 crystals 5×5×5 cm^3, 0.75 kg each)
- Mass of TeO_2: 741 kg (~206 kg of ^{130}Te)
- Energy resolution: 5 keV @ 2615 keV (FWHM)
- Stringent radiopurity controls on materials and assembly
- Operating temperature: ~ 10 mK
- Mass to be cooled down: ~ 15 tons (lead, copper and TeO_2)
- Background aim: 10^{-2} c/keV/kg/year
- $T_{1/2}$ sensitivity (90% C.L.): 0.95 x 10^{26} yr



Thermal detectors



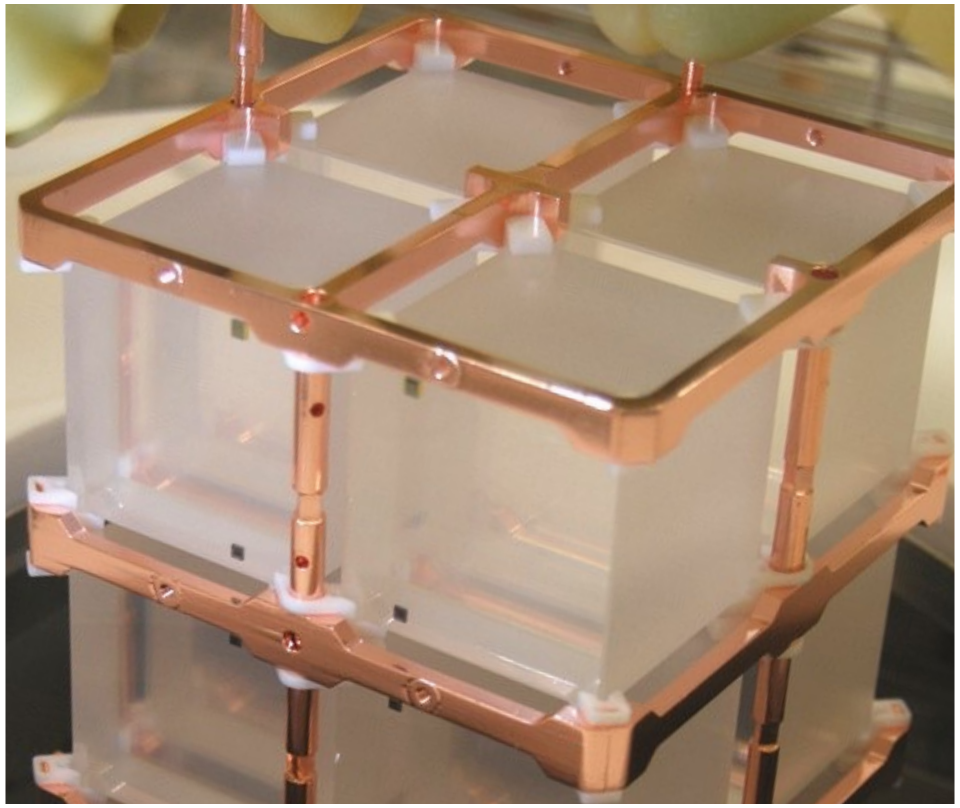
heat bath (~10mK)

weak thermal coupling

Thermistor
(Ge-NTD)

$C \propto T^3$

Absorber crystal
(TeO_2)



- wide choice of detector materials

  low heat capacity @ T_{work}

- excellent energy resolution (~1 ‰ FWHM)

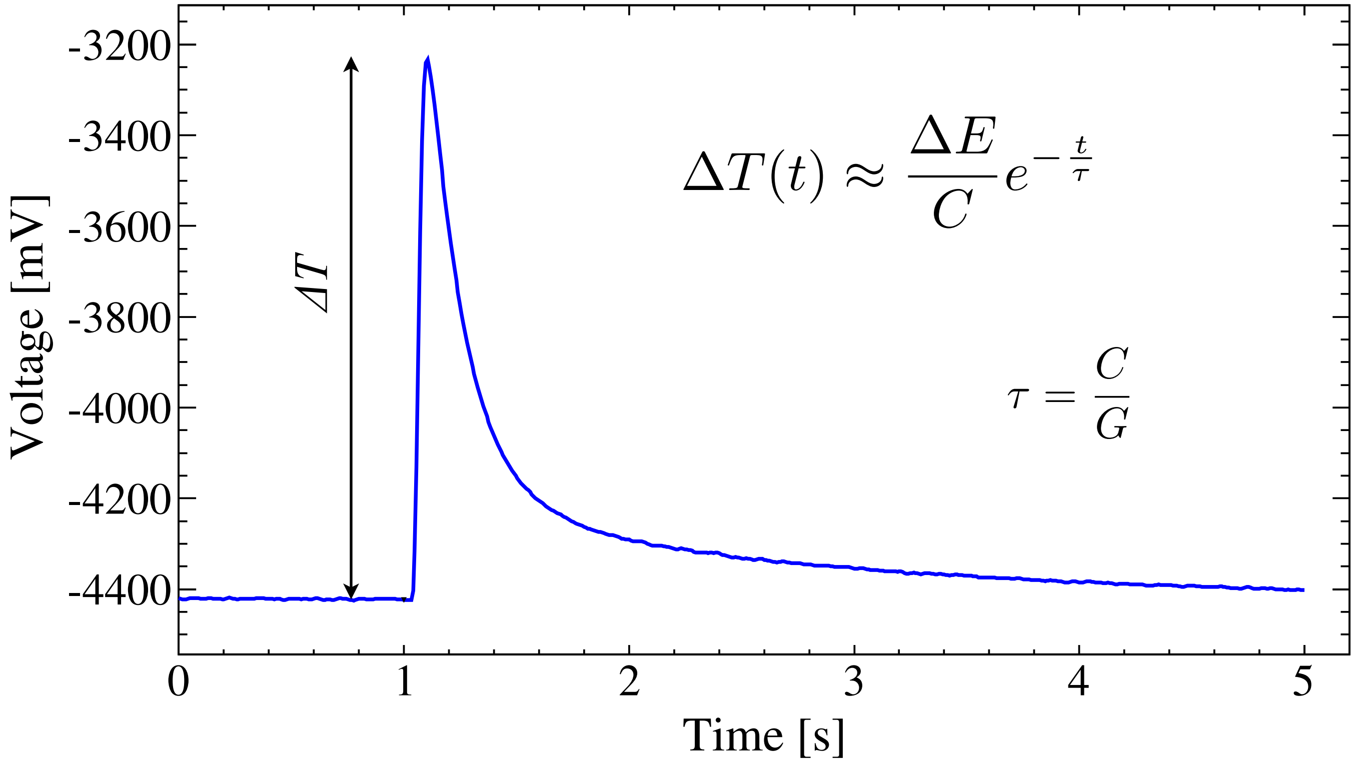
  huge number of energy carriers (phonons)

- equal detector response for different particles

  true calorimeters

- slowness

  in rare event search doesn't matter



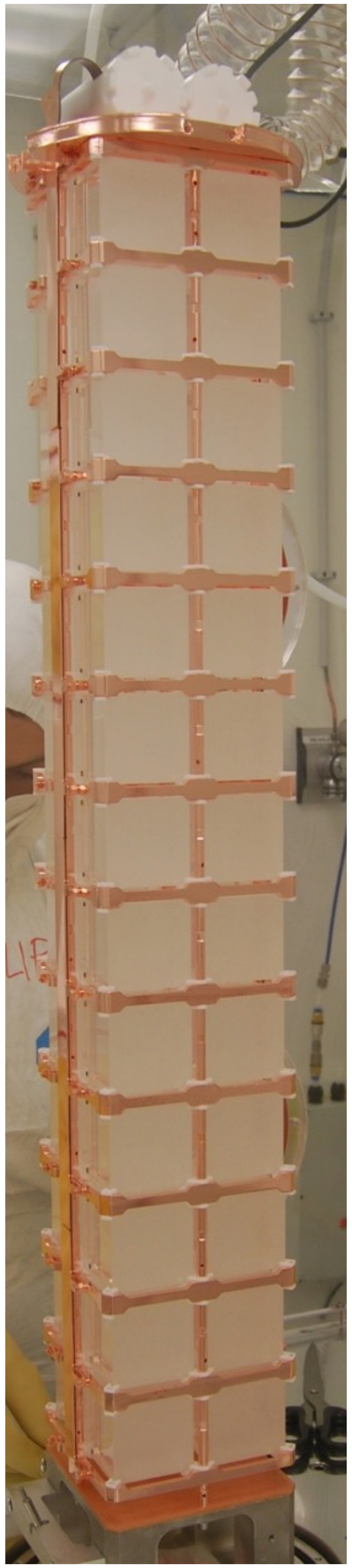
$$\Delta T(t) \approx \frac{\Delta E}{C} e^{-\frac{t}{\tau}}$$

$$\tau = \frac{C}{G}$$

CUORE-0

CUORE-0 is the first tower produced out of the CUORE assembly line.

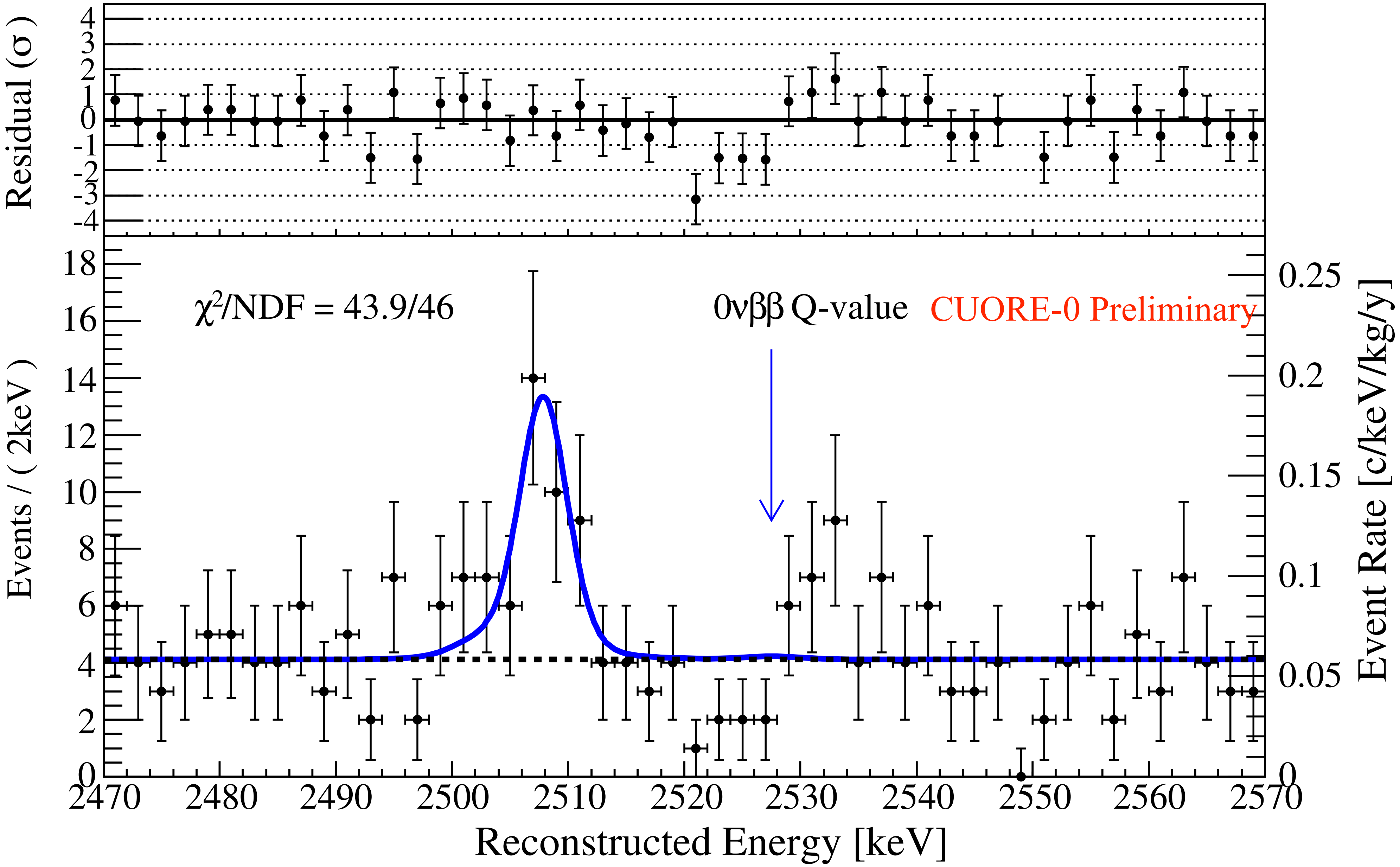
- 52 TeO_2 5x5x5 cm^3 crystals (~750 g each)
- 13 floors of 4 crystals each
- total detector mass: 39 kg TeO_2 (10.9 kg of ^{130}Te)



CUORE-0 has been taking data since March 2013 in the 25 year old Cuoricino cryostat.

- Proof of concept of CUORE detector in all stages
- Test and debug of the CUORE tower assembly line
- Test of the CUORE DAQ and analysis framework
- Check of the radioactive background reduction
- Extend the physics reach beyond Cuoricino while CUORE is being assembled
- Sensitive 0ν-ββ experiment

CUORE-0 results

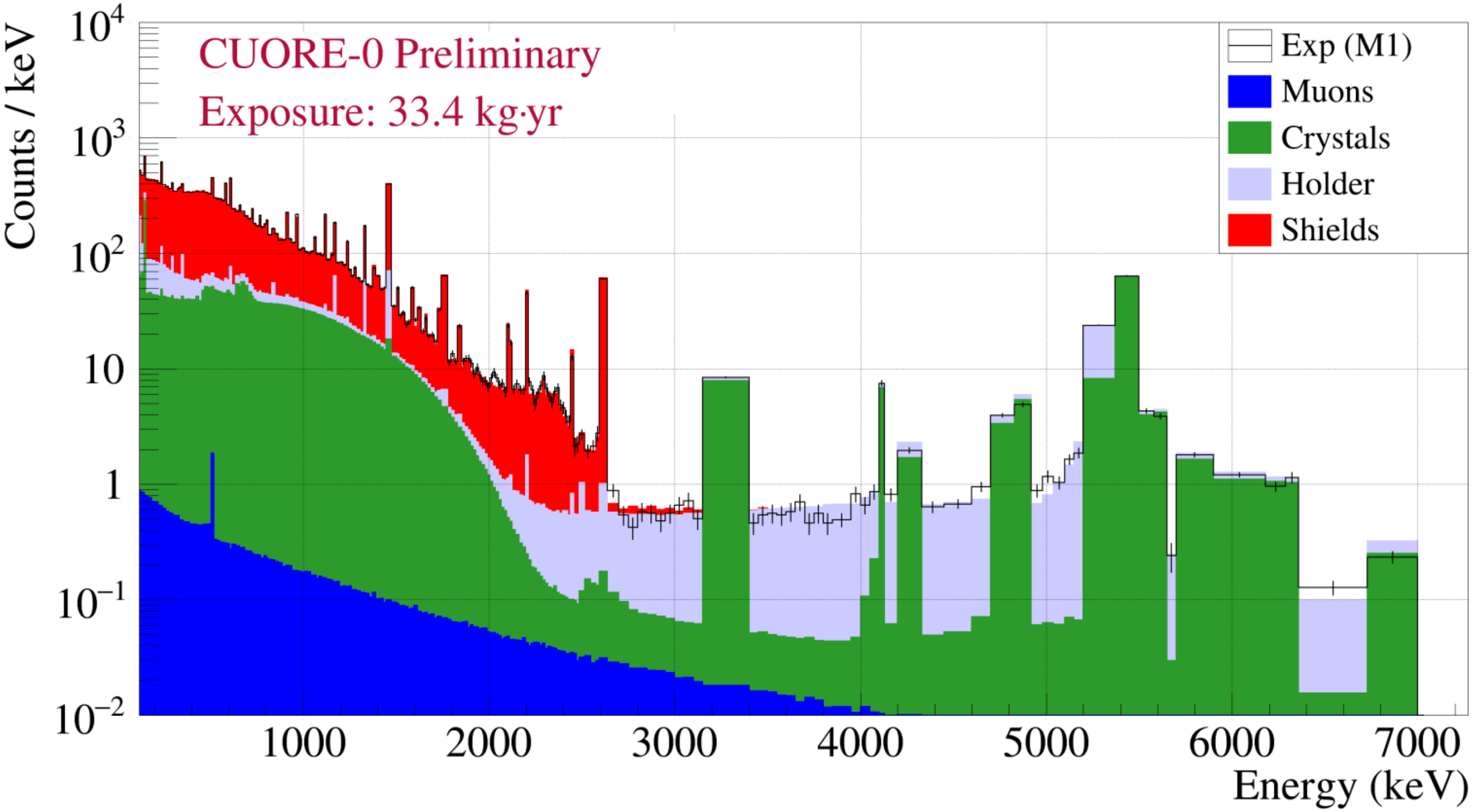


Background index: 0.058 ± 0.004 (stat.) ± 0.002 (syst.) c keV^{-1} kg^{-1} yr^{-1}

0ν-ββ ^{130}Te Bayesian 90% C.L. limit: $T_{1/2} > 2.7 \times 10^{24}$ yr

<$m_{\beta\beta}$> < (270-650) meV

CUORE-0 background reconstruction



0νββ ROI background:

- Shields: ~72%
- Holder: ~21%
- Crystals: ~5%
- Muons: ~2%

- In CUORE the contribution from the cryostat shields will be strongly reduced
- Main background will come from degraded alpha particles

CUORE Towers Assembly

- Assembly of all the 19 CUORE towers completed in 2014

Assembly line improved

after CUORE-0

CUORE-0

51/52 NTD connected

51/52 heaters connected

CUORE

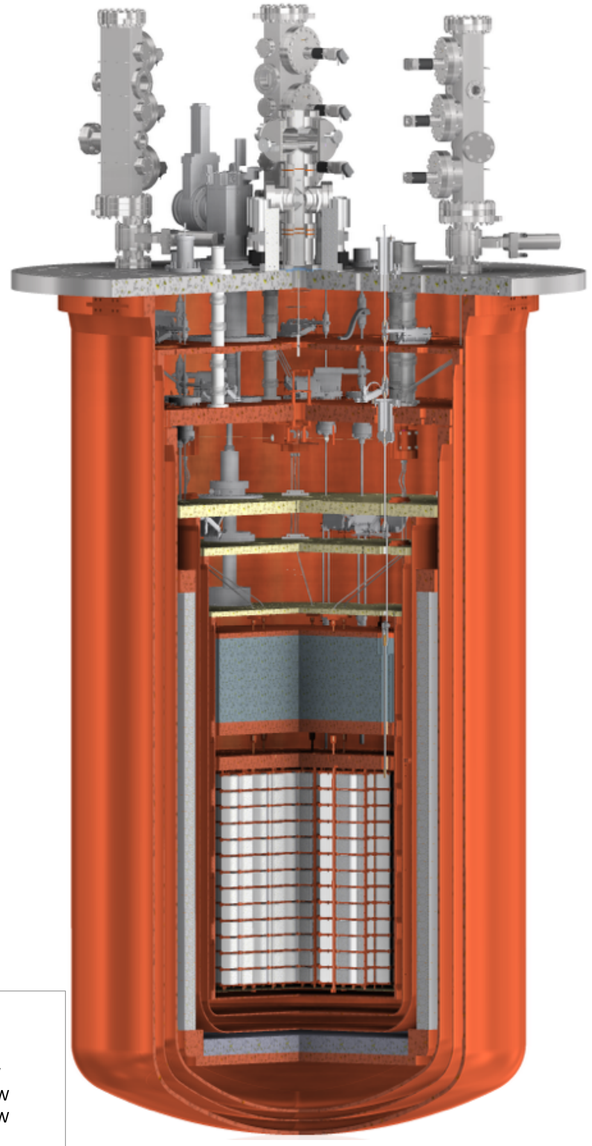
988/988 NTD connected

988/988 heaters connected

- Also a mockup tower for the Detector installation phase and a minitower to be used during the cryostat commissioning runs were produced

Cryogenic system commissioning: phase 1

Phased commissioning adding complexity at each step

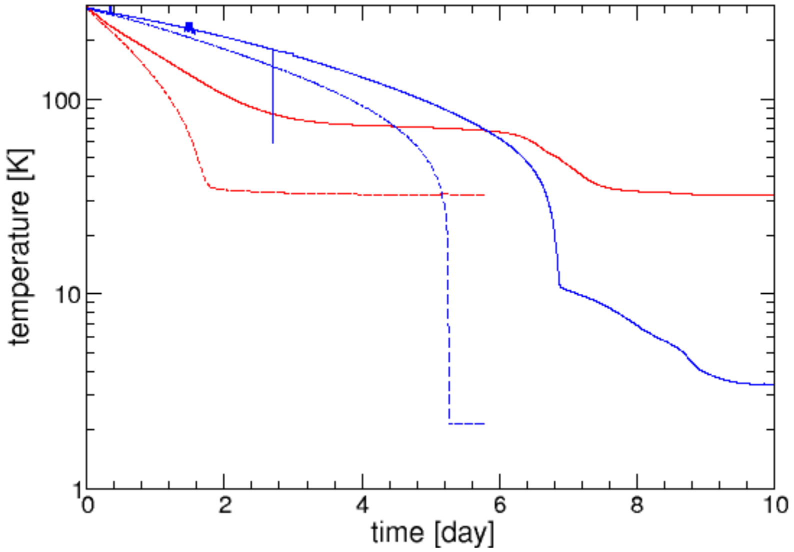


- Phase I: individual systems test
  - Outer/Inner vacuum chamber
  - Cryostat

    Final temperatures:

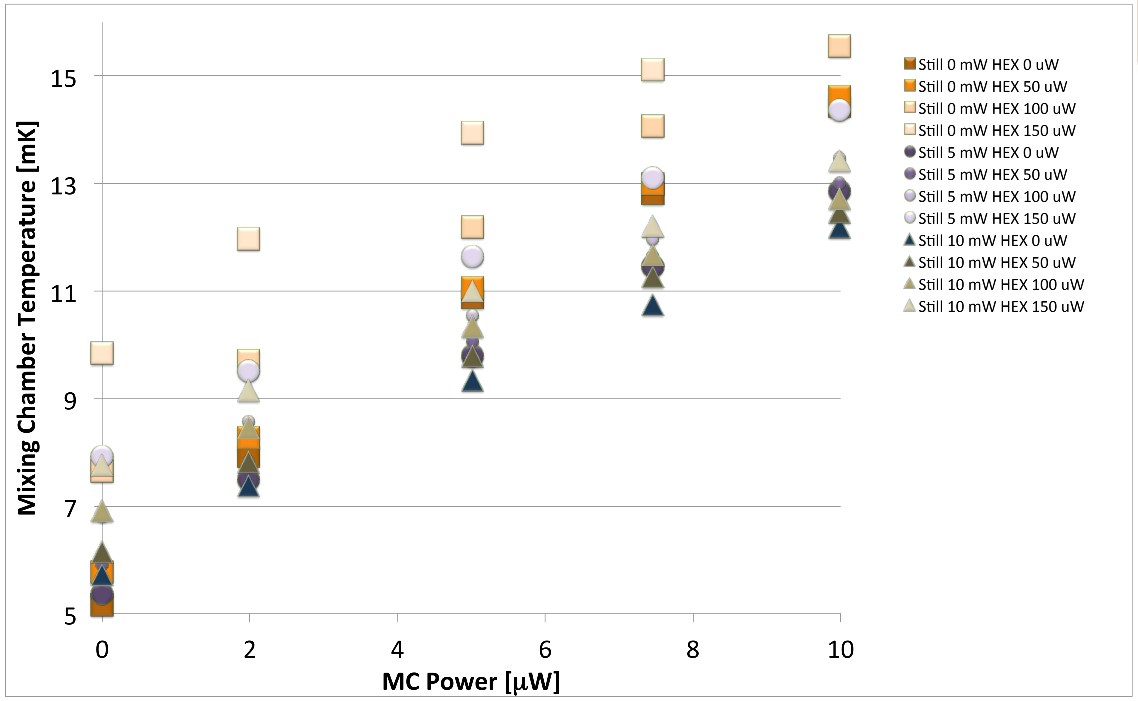
      32 K at the 40K stage

      3.3 K at the 4K stage



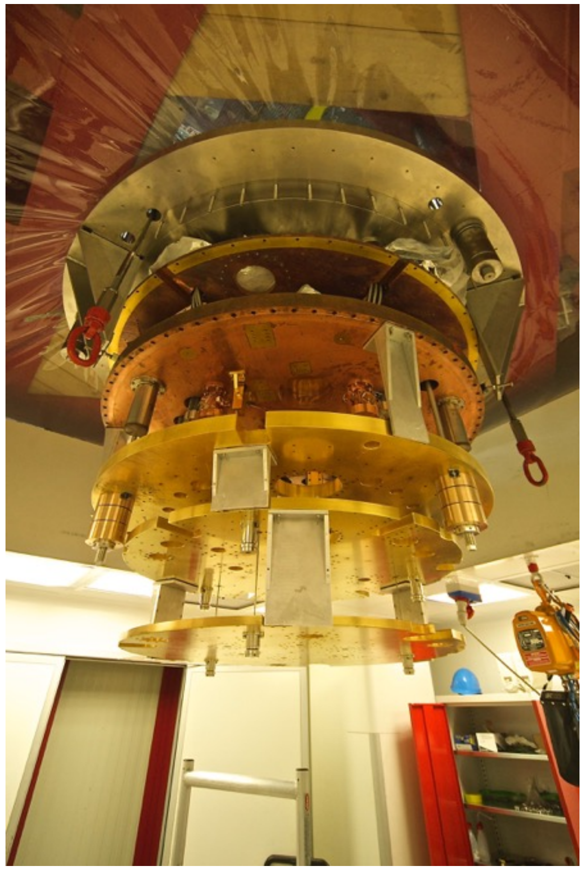
  - Dilution Unit

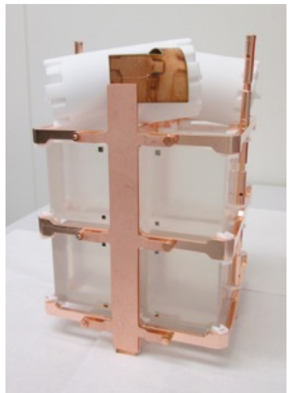
    Lowest temperature: 4.95 mK



- Phase II: system integration

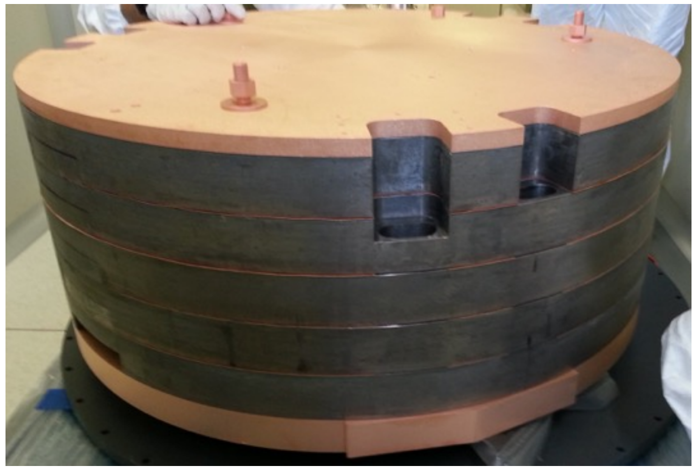
Cryogenic system commissioning: phase 2





Insertion of few TeO_2 detectors

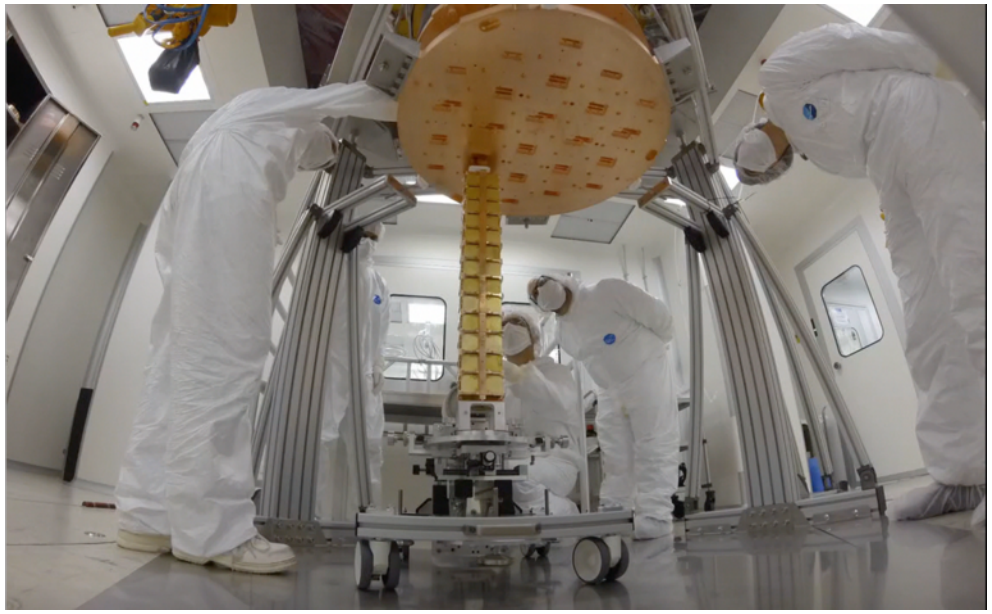
↓

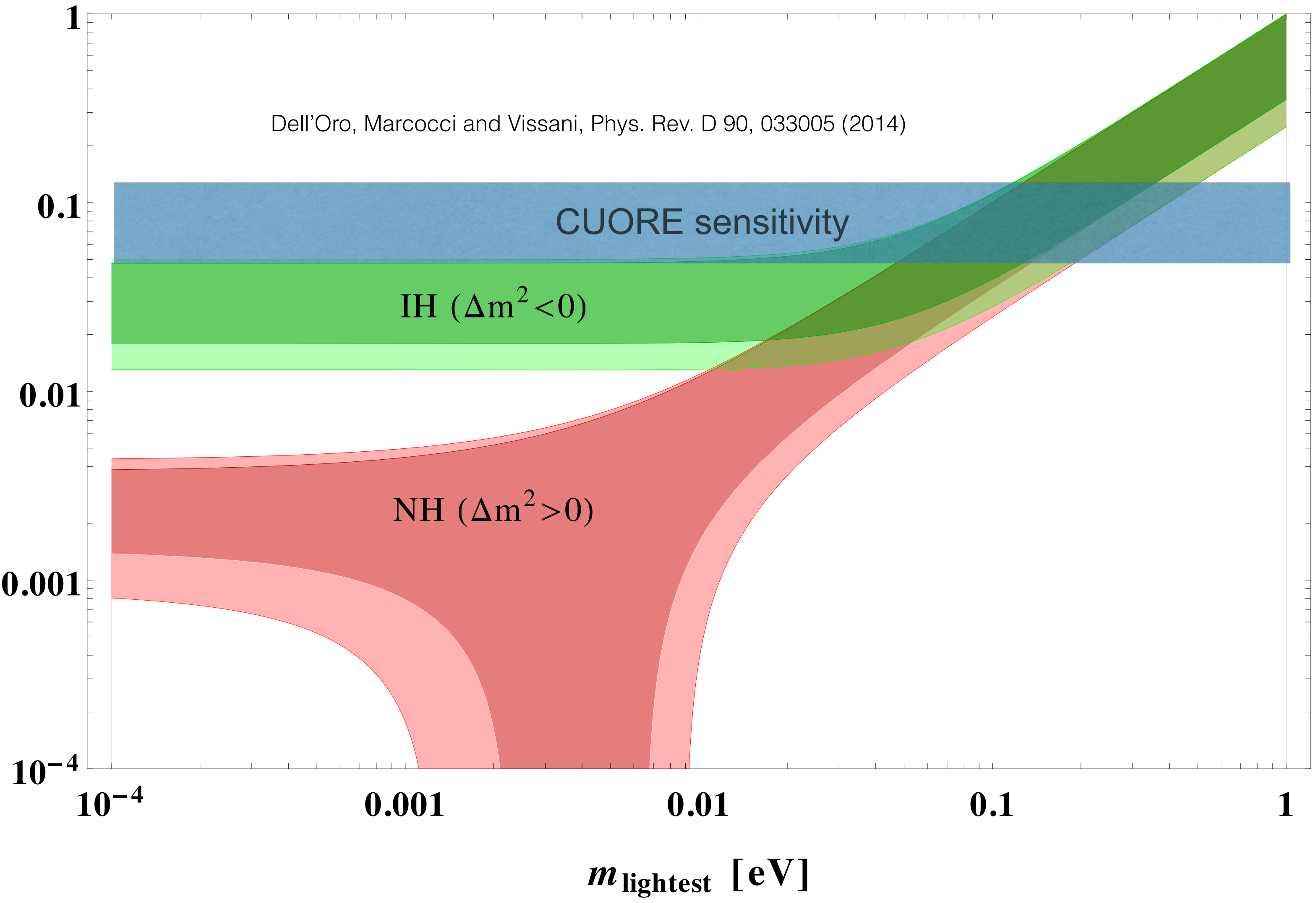


Cryostat + Dilution Unit → Wiring → Top Pb shield / Detector Calibration System / Towers support plate / Fast Cooling System → side roman Pb shield

Present Status

- Cryogenic commissioning is completed
- Installation of all the 19 CUORE towers in the cryostat will start in 3 weeks
- CUORE cooldown foreseen in October





Dell'Oro, Marcocci and Vissani, Phys. Rev. D 90, 033005 (2014)

- $T_{1/2}$ sensitivity 0.95×10^{26} years @ 90% C.L. (5 years)
- $m_{\beta\beta}$ sensitivity 50-130 meV @ 90% C.L. (5 years)

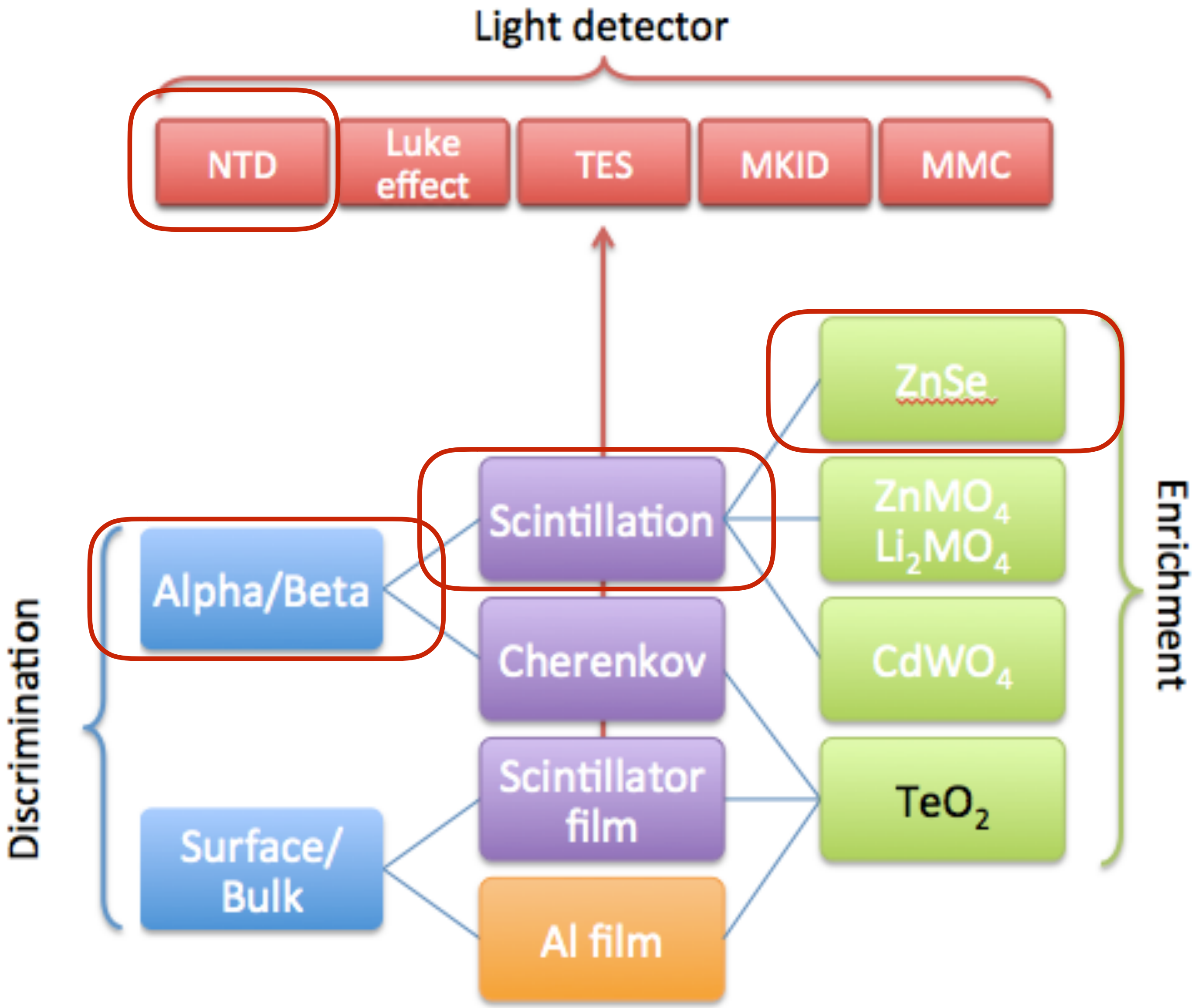
CUPID

- CUPID (CUORE Upgrade with Particle IDentification) aims at the realization of a ton-scale bolometric 0ν-ββ experiment, based on the experience learned in CUORE.
- CUPID plans to use the CUORE infrastructure @ LNGS, once CUORE completes operation
- Several R&D in progress

Required upgrades

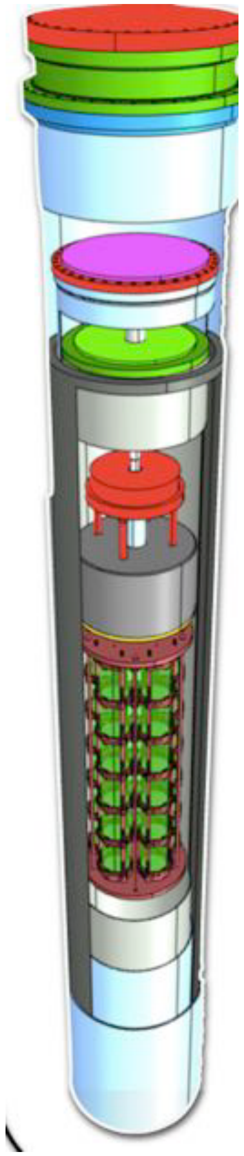
- background discrimination
- isotopic enrichment
- stricter material selection
- possibly new shielding concepts

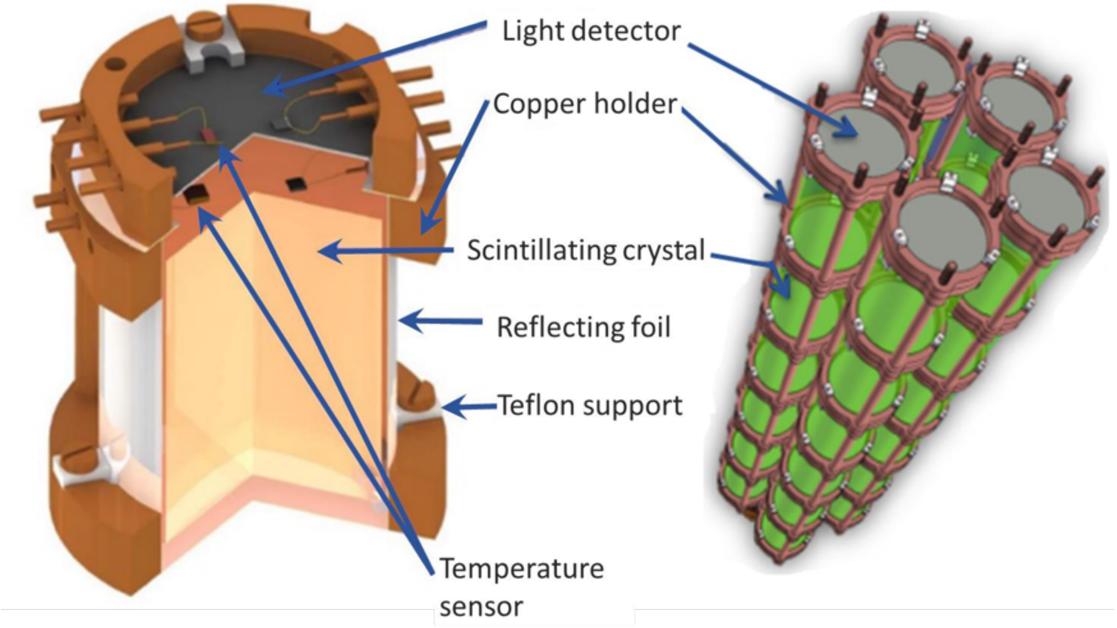
Phased program to test different techniques in small scale demonstrators

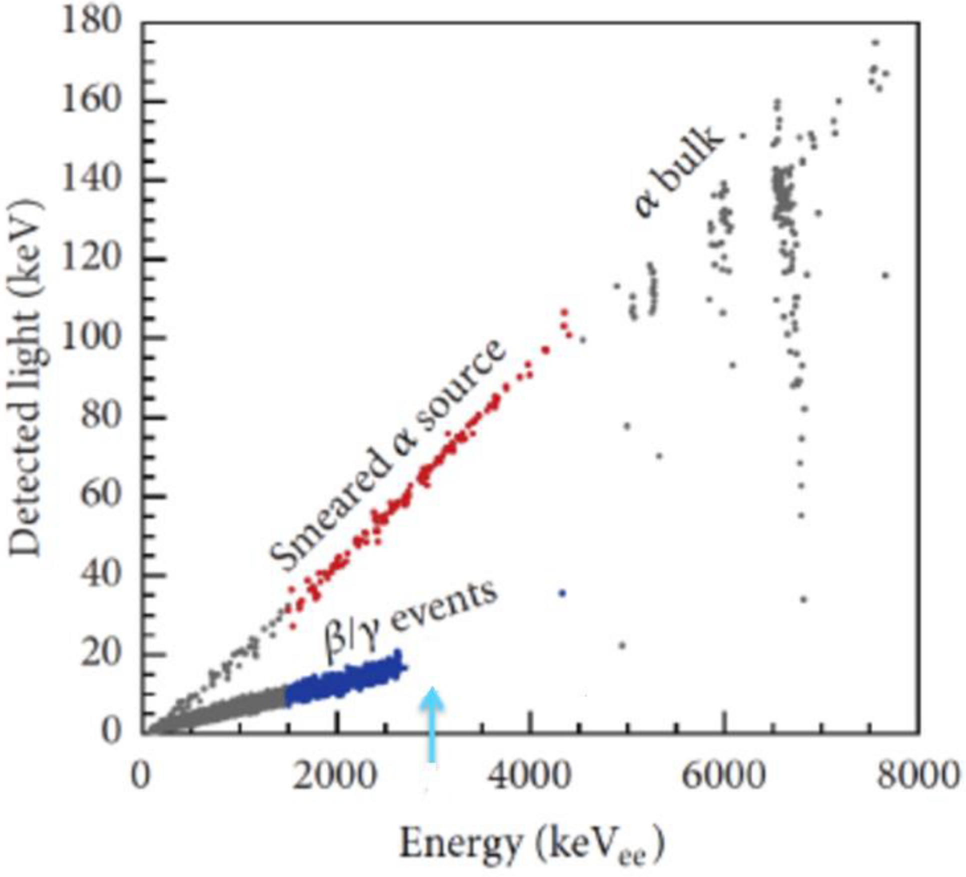


R&D towards CUPID: arXiv:1504.03612 CUPID : arXiv:1504.03599

First demonstrator: CUPID-0/LUCIFER

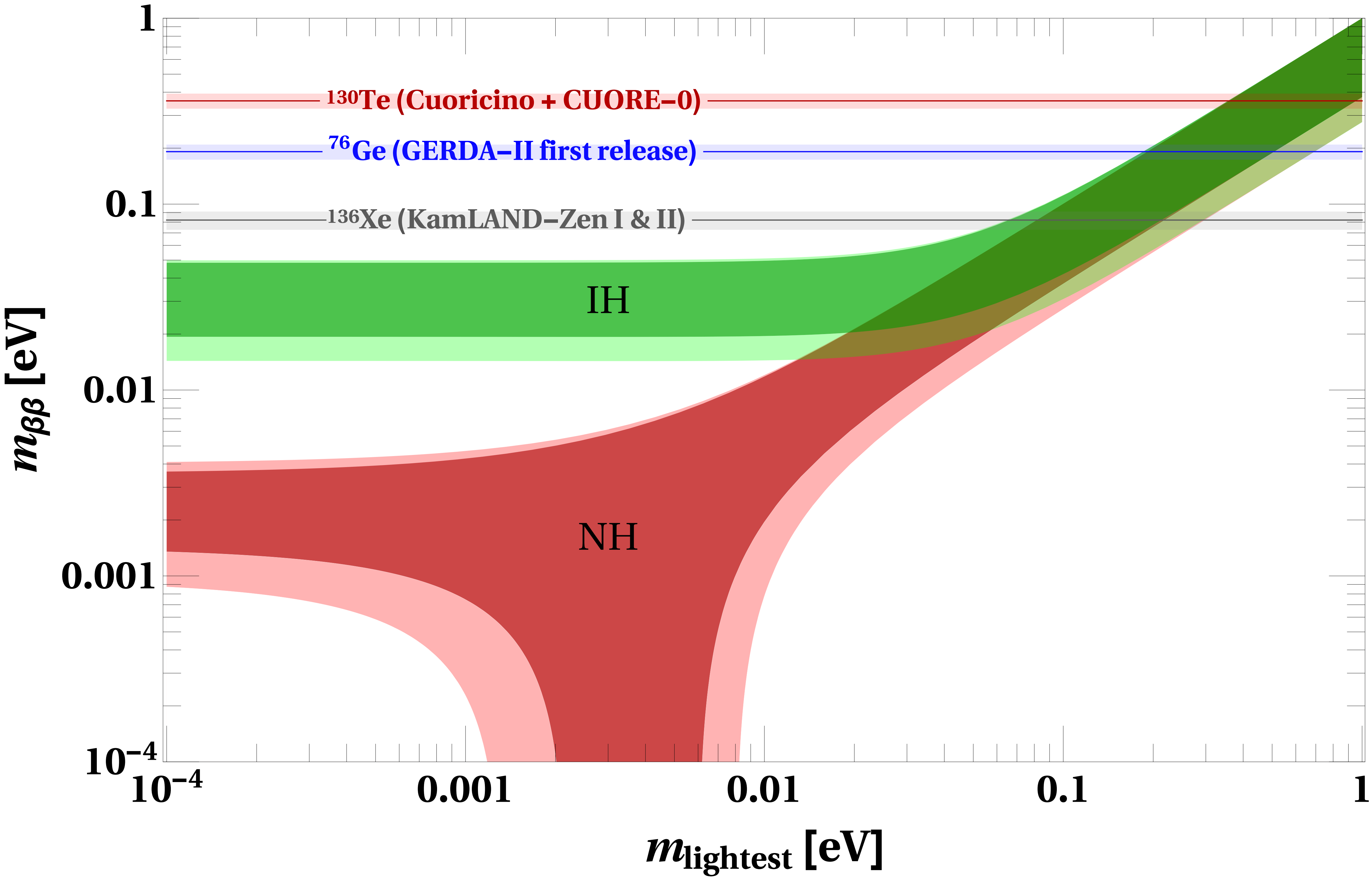




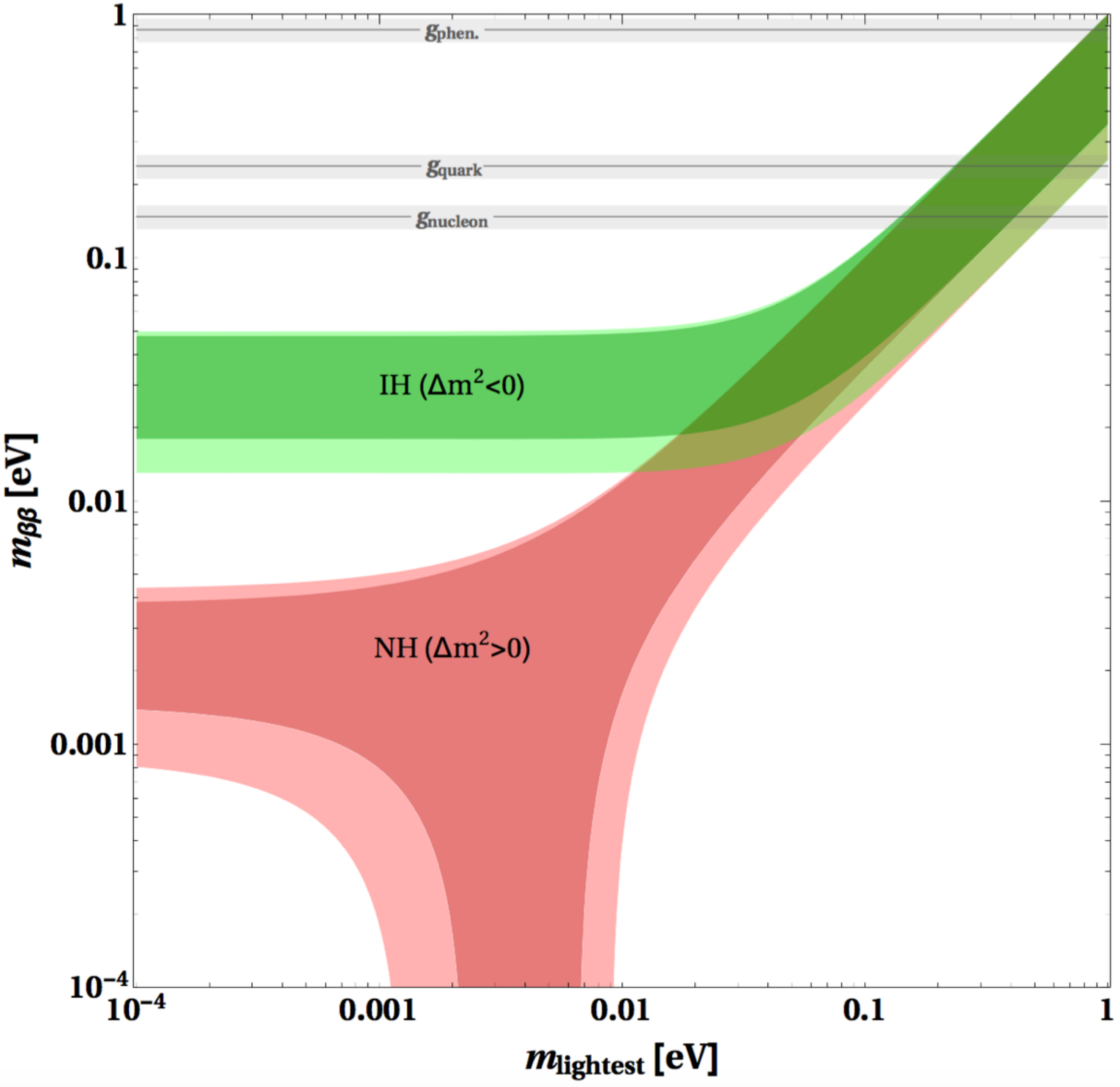


- 30 Zn^{82}Se crystals ~440 g each @ 95% enrichment operated as scintillating bolometers
- Bolometers arranged in 5 towers and faced to Ge light detectors
- Total mass: 13.2 kg (7 kg ^{82}Se)
- Expected bkg @ ROI 10^{-3} c/keV/kg/y
- Expected energy resolution @ ROI: 10 keV FWHM
- Data taking: Autumn 2016

Present limits on mββ



Importance of the g_A quenching



Dell'Oro, Marcocci and Vissani, Phys. Rev. D 90, 033005 (2014)

$$t_{0\nu}^{1/2} \propto \mathcal{M} = g_A^{-4} \mathcal{M}_{0\nu}^{-2}$$

$$g_A = \begin{cases} g_{A,\text{ nucleon}} & = 1.269 \\ g_{A,\text{ quark}} & = 1 \\ g_{A,\text{ phen.}} & = 1.269 \cdot A^{-0.18} \end{cases}$$

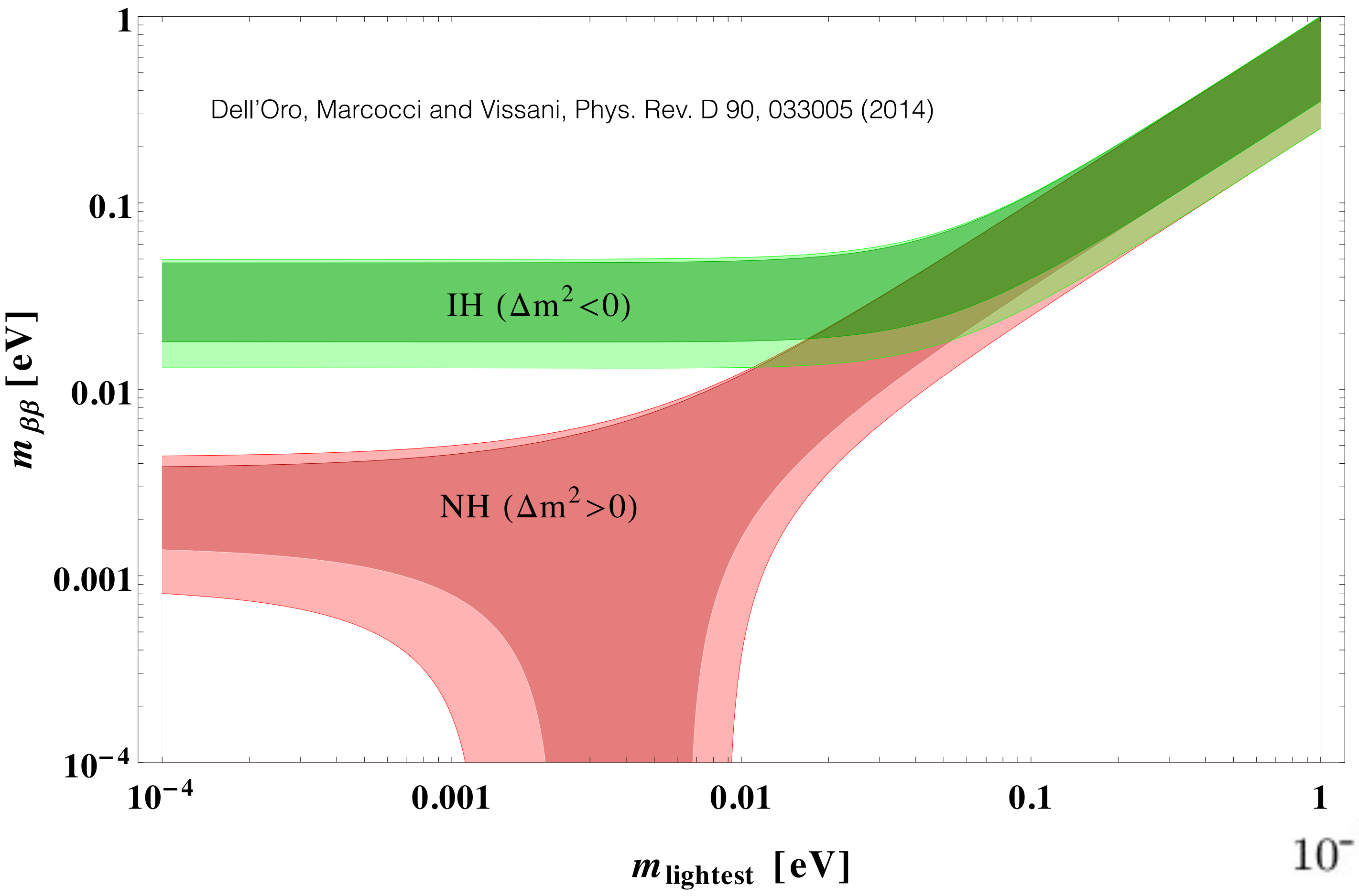
g_A	$m_{\beta\beta}^{\text{min}}$ [eV]
$g_{A,\text{ nucleon}}$	0.15 ± 0.03
$g_{A,\text{ quark}}$	0.24 ± 0.05
$g_{A,\text{ phen.}}$	0.87 ± 0.17

NMEs (IBM-2): J. Barea *et al.*, **Phys. Rev. C 91, 034304 (2015)**

PSFs: J. Kotila & F. Iachello, **Phys. Rev. C 85, 034316 (2012)**

^{136}Xe: A. Gando *et al.*, **Phys. Rev. Lett. 110, 062502, (2013)**

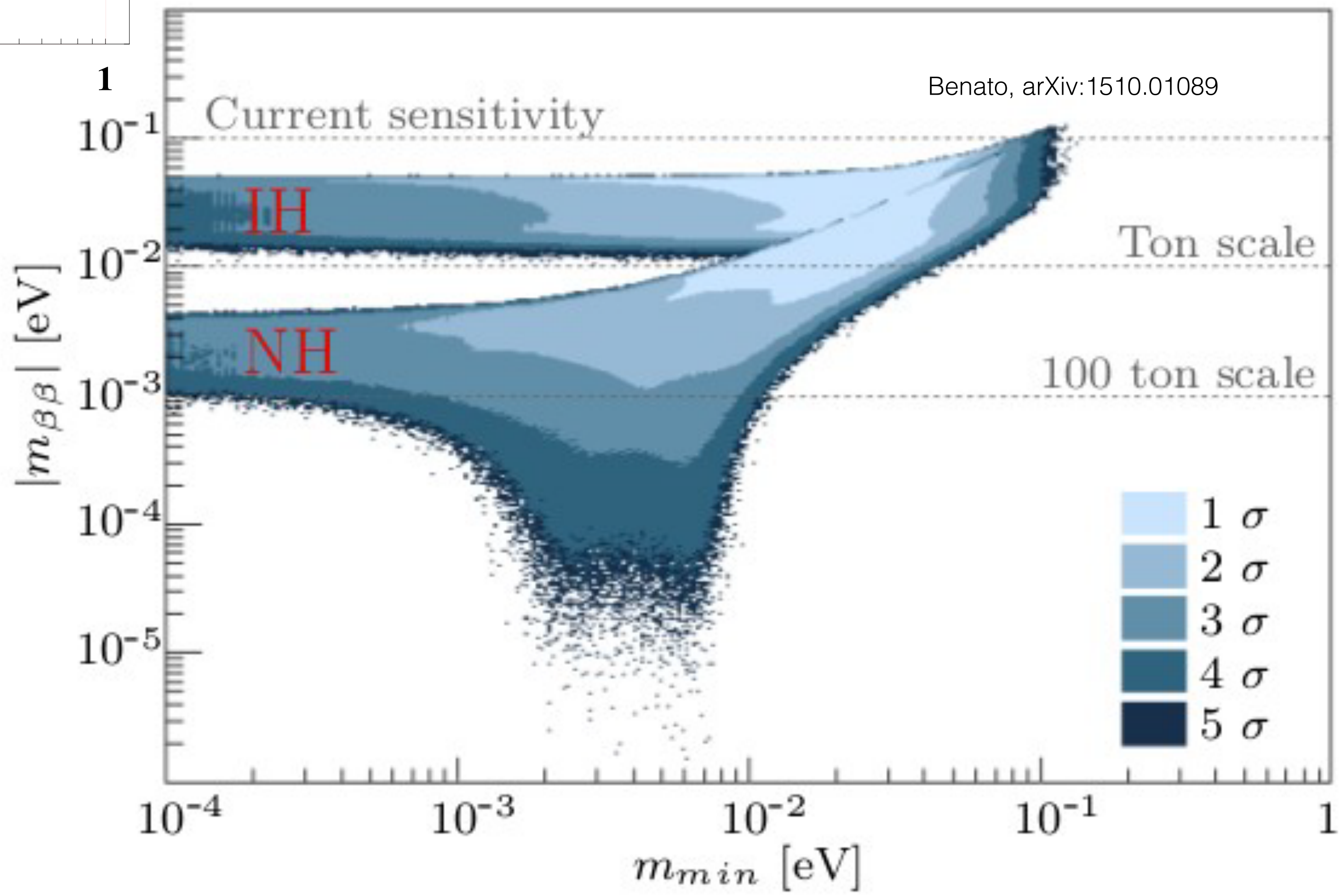
Normal hierarchy is unreachable?



Dell'Oro, Marcocci and Vissani, Phys. Rev. D 90, 033005 (2014)

- Data from oscillations experiments
- Main uncertainty given by the Majorana phases

- Toy Montecarlo
- Bound on the sum of neutrino masses from cosmology
- Flat probability distribution for Majorana phases



Benato, arXiv:1510.01089

Conclusions

- Very strong worldwide competition, many results in the last months (and others to come)
- 0ν-ββ discovery could be within reach
  - If nothing is found we have to go to larger target mass
  - more money (about 50-100 M€)
  - isotopic enrichment will be the dominant cost
  - IMHO worthwhile
- improvement in NME calculation and especially better knowledge on g_A is advisable
- LNGS has a relevant role in 0ν-ββ